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ANALYSIS, APPROACH AND ASSESSMENT OF VIBRATION CRITERIA IN SHIPBOARD MACHINERY CONDITION MONITORING AND DIAGNOSTICS

by

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ABSTRACT (Maximum 200 words)

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SUBJECT TERMS

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ABSTRACT

The setting of alarm levels plays a vital role in a machinery condition monitoring and diagnostic system. In this research, two approaches to setting vibration alarm levels using vibration signals produced by fire pumps are presented in the time and frequency domains. In the time domain, the cross peak analysis (CPA) is proposed to extract the dominate peak points. The distribution of these cross peak points is found to have a lognormal distribution and can be normalized to a Normal distribution in the VdB domain. The computed $\mu+2\sigma$ value in the VdB domain is suggested for use as the alarm level. In the frequency domain, the 1/1 octave band analysis (OBA) is introduced. Three artificial fault simulations are conducted to compare the 1/1 octave band method with the broadband method. The results show that the 1/1 octave band method is more sensitive to the changes in VdB level than the broadband method. The computer programs to perform these two analyses are written using MATLAB. Examples of the use of these programs are included in this report.

TABLE OF CONTENTS

I. INTRODUCTION

In recent years, the rising cost of machine maintenance has driven engineers to develop more economical and efficient methods to determine machine health and to plan accordingly the required preventive and corrective maintenance. The most popular technique in use today is a predictive maintenance program based on condition monitoring. In naval applications, condition monitoring is commonly achieved utilizing vibration measurement and analysis on-board surface ships and submarines [Refs. 1-7].

This research focuses on the use of vibration measurement to monitor machine health and to diagnose system problems which could lead to machine failure. In addition to providing accurate and understandable data on the machine's current condition, a monitoring and diagnostic system must also limit the number of false alarms. Alarm threshold settings are vitally important in machine vibration diagnostics. Alarm thresholds set too high may result in premature machine failure caused by an undetected failure condition. Alarm thresholds set too low may result in frequent false alarms causing unnecessary system interruptions and repairs. False alarms also reduce operator confidence in the monitoring and diagnostic system.

Because the optimum setting of alarm thresholds in vibration monitoring and diagnostic systems continues to be problematical, the goals of this research were:

- To establish a statistical analysis method for setting vibration alarm levels by using time domain data.

• To investigate the difference in broadband alarm levels between the cross peak method and vibrometer readings.

• To perform a 1/1 octave band analysis for setting vibration alarm levels by using time and frequency domain data.

Chapter II provides the background information on the machinery utilized in this research and a discussion of alarm level setting. Chapter III describes the procedure of data acquisition and processing and the methods of analysis. In the time domain, a statistical analysis method using "cross peak" data is introduced. In the frequency domain, a 1/1 octave band concept is used to set alarm levels. The test results and observations using time domain data are presented in Chapter IV. Three types of shipboard fire pumps were analyzed using time and frequency data. Three artificial fault simulations were performed to assess the 1/1 octave band method. Chapter V demonstrates the 1/1 octave band analysis results using the NAVSSES frequency domain database. Chapter VI contains conclusions and recommendations for further research.

II. BACKGROUND

A. DATA SOURCE

The fire pump on a naval ship provides more than fire fighting water to damage control systems. The seawater provided by fire pumps is also used by vital air conditioning and chill water systems, main drainage systems and decontamination sprinkler systems. At least one fire pump is running whenever a ship is underway or at anchor. In this research, twenty-three fire pumps from four classes of ships are grouped into three types in Table 1.

Table 1: CLASSIFICATION OF FIRE PUMP DATA

Hull Number	Date of Survey	Number of Fire Pumps	Number of Pickup Locations	Number of Data Sets	Type
CG-59	10/30/89	6	5	30	I
CG-59	2/26/90	6	5	30	
DDG-994	N/A	3	5	15	II
FF-1062	11/24/89	4	5	20	III
FF-1071	3/10/89	4	5	20	

The vibration velocity signals were measured by means of transducers strategically placed at pickup locations on the pumps. Schematic layouts of each fire pump and pickup locations are depicted in Figures 1 through 3. A list of abbreviation for pickup locations is shown in Table 2. The transducer pickup placement is uniaxial with one radial pickup at each bearing and one axial pickup at the thrust bearing. This arrangement is listed in the Vibration Test and Analysis Guide (VTAG) [Ref.8]. This guide provides the most current technical information for each machine in a particular ship class and includes information on pickup locations, operating conditions and a table of vibration source components. Table 3 through Table 5 summarize the vibration source components. These tables identify exciting elements within each machine and list the vibration frequencies generated by each element. The vibration frequencies were normalized as multiples of the machine's rotation rate, called "orders". The time waveforms are recorded on magnetic tape by a frequency modulated (FM) recorder. Each pickup location on the pumps was recorded for a one minute time series record. Some of the important specifications of the tape recorder are provided in Table 6.

In addition to the data tapes, six survey dates of data in ASCII form were received from the NAVSSES database. These data contain the frequency spectrum levels measured by vibrometer.

TABLE 2: ABBREVIATIONS OF PICKUP LOCATION

Abbreviation	Description
MB(FE)	Motor Bearing (Free End)
MB(CE)	Motor Bearing (Coupling End)
MB(CE/A)	Motor Bearing (Coupling End/Axial direction)
PB(FE)	Pump Bearing (Free End)
PB(CE)	Pump Bearing (Coupling End)
PB(CE/A)	Pump Bearing (Coupling End/Axial direction)
UMB	Upper Motor Bearing
LMB	Lower Motor Bearing
LMB(A)	Lower Motor Bearing (Axial direction)
UPB	Upper Pump Bearing
LPB	Lower Pump Bearing

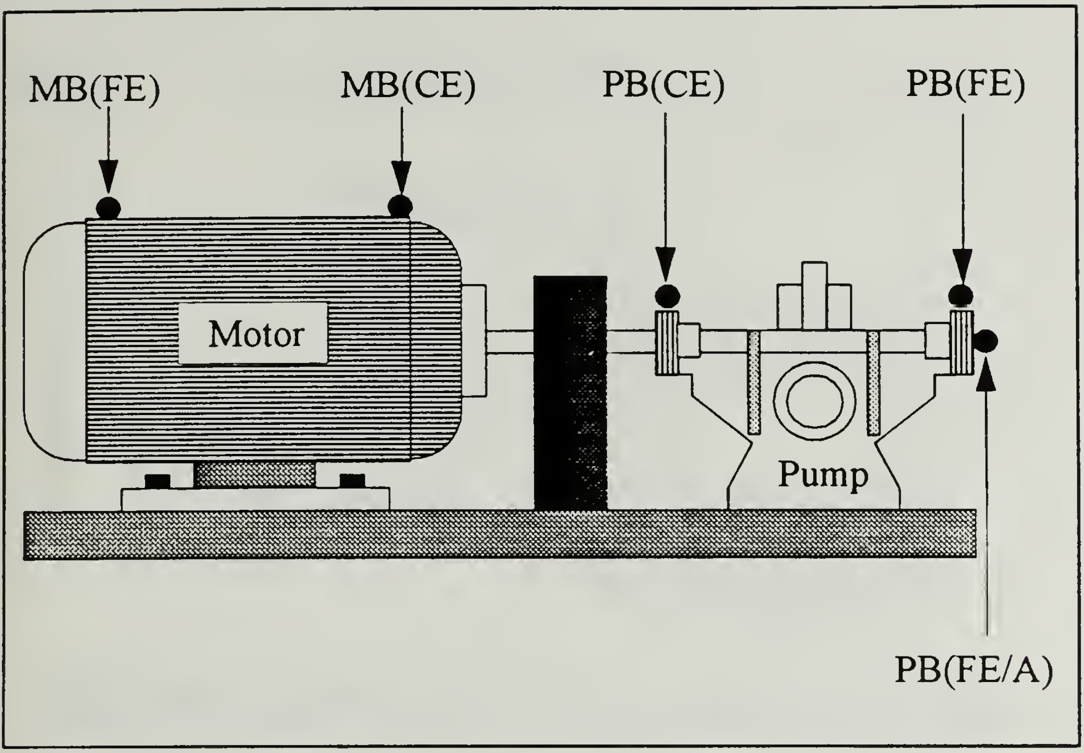


Figure 1 Schematic Layout of a CG-59 Fire Pump

TABLE 3: CG-59 VIBRATION SOURCE COMPONENTS

Driver (Motor)			Driven (Pump)		
Description	Element	Order	Description	Element	Order
Motor Shaft (Ref.)		1	Pump Shaft		1
Fan Blading	5	5	Impeller Vanes	6	6
Slots	54	54	Bearing	FAG WT	
Bars	44	44			
Poles	2	2			
Bearing	MRC 310				
Bearing	MRC 311				

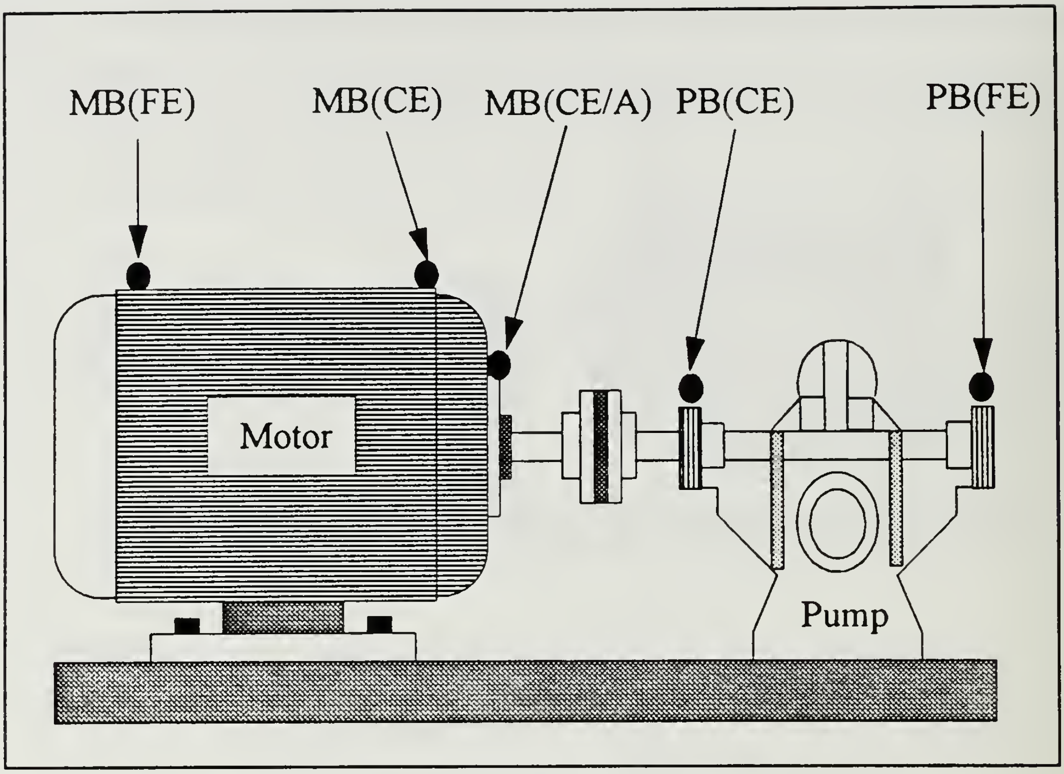


Figure 2 Schematic Layout of a DDG-994 Fire Pump

TABLE 4: DDG-994 VIBRATION SOURCE COMPONENTS

Driver (Motor)			Driven (Pump)		
Description	Element	Order	Description	Element	Order
Motor Shaft (Ref.)		1	Pump Shaft		1
Fan Blading	7	7	Impeller Vanes	5	5
Slots	48	48	Bearing	SKF 306	
Bars	38	38			
Poles	2	2			
Bearing	MRC 310				
Bearing	MRC 311				

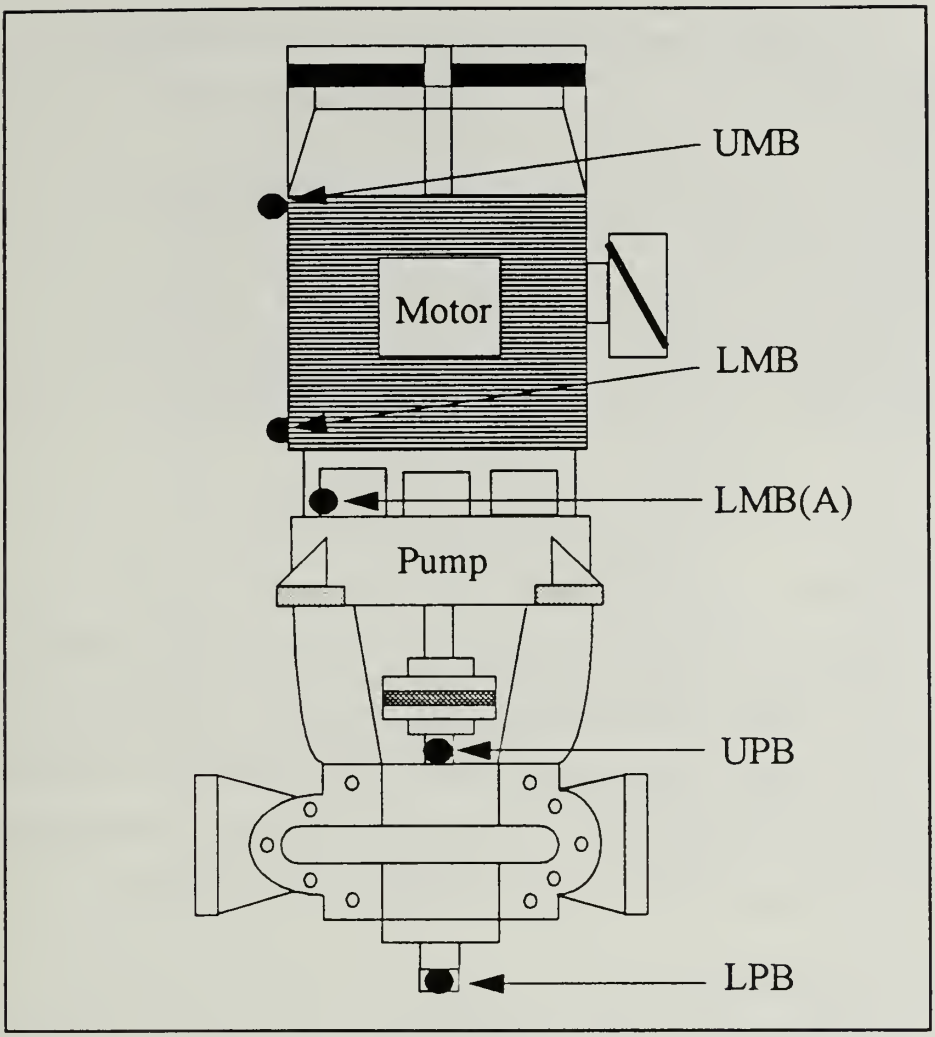


Figure 3 Layout of a FF-1062 / FF-1071 Fire Pump

TABLE 5: FF-1062 / FF-1071 VIBRATION SOURCE COMPONENTS

Driver (Motor)			Driven (Pump)		
Description	Element	Order	Description	Element	Order
Motor Shaft (Ref.)		1	Pump Shaft		1
Poles	2	2	Impeller Vanes	5	5
Bearing	Ball Bearing		Bearing	SKF 6307	

TABLE 6: SPECIFICATIONS OF FM RECORDER

Manufacture	Dallas Instruments Inc.
Model	4800 FM Recorder
Frequency Response	2 to 5000 Hz within 1 dB
Signal to Noise Ratio	40 dB rms
Harmonic Distortion	No harmonic above -40 dB
Tape Type	TDK AD C60 cassette

B. Alarm Level

The fundamental question that must be answered before vibration condition monitoring can be used as a diagnostic tool for machinery is what alarm levels identify operation-limiting faults. Generally, the vibrations of a system can be characterized by a reduced data set in various domains. The criteria used to set alarm levels can be considered either in the time domain or the frequency domain, as discussed below.

1. Time Domain Criteria

a. Vibration Severity Criterion Method

The simplest time domain method is the vibration severity criterion. The root mean square (RMS) value of vibration velocity is usually measured and compared with vibration severity charts [Ref. 9]. Figure 4 shows the vibration severity chart that was first introduced by T. C. Rathbone in 1939 and then later refined by the Instrument Research and Development Corporation. Various national standard organizations have also published standards for judging vibration severity. For example, International Standards Organization (ISO) standards 2372 and 3945 provide severity guidelines for machinery.

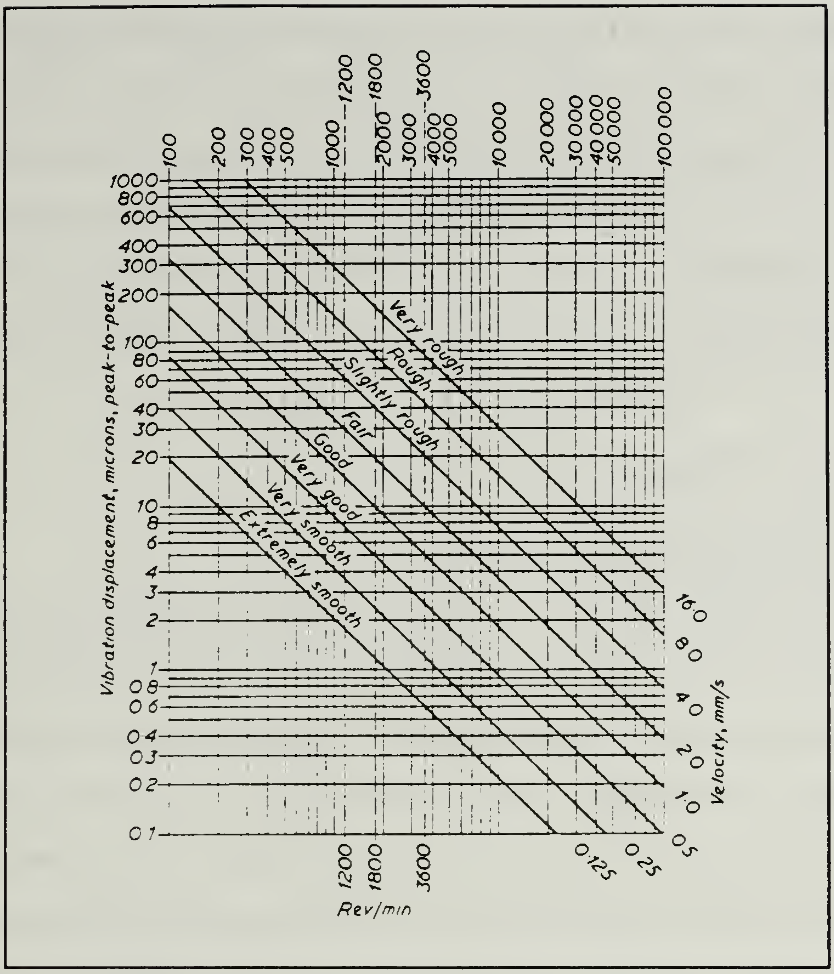


Figure 4 General Machinery Vibration Severity Chart [Ref. 9]

The disadvantages in using these criteria are [Ref. 10]:

• The criteria can be used only for specific types of machinery at a standard operating condition.

• No diagnostic information is provided.

• The criteria are less sensitive during the early stages of damage.

Thus, the vibration severity criterion method can be only used as a rough indicator of machinery health.

b. Amplitude Probability Criterion Method

A More sophisticated method was developed using statistical analysis to examine the distribution of vibration amplitudes. The amplitudes used can be either peak-to-peak, peak or RMS readings of displacement, velocity or acceleration. Both Campel [Ref. 11] and Murphy [Ref. 12] use this statistical method to establish alarm levels based on the mean of the reading plus 3 standard deviations. The key drawback of this approach is that it assumes that a Normal distribution of the linear readings exists. Vibration readings have a "skewed" rather than "Normal" distribution [Ref. 13].

2. Frequency Domain Criteria

a. Broadband Criterion Method

The broadband criterion method utilizes a vibrometer which can add all the energy dissipated over a wide frequency range (typically 10 to 10,000 Hz). The overall energy is typically calculated by applying the RMS summation method to the spectrum. If the overall energy level exceeds a predetermined level, then alarms are triggered. This is a simple and effective method in most cases. But in some cases may be inadequate because it is less sensitive to small changes associated with bearing defects in the presence of large amplitude frequency components. This limitation can be overcome by using the octave band or narrow band method.

b. Octave Band Criterion Method

The octave band criterion method is often used in acoustics to determine the energy level changes due to noise and vibration. This method utilizes a constant percentage bandwidth to divide the frequency range of interest into several bands which provide more detailed information than the broadband presentation. A commonly used bandwidth is the one-third octave band. Early researchers used this method to check the change in each band level and determine if the amplitudes exceeded normal values [Ref. 14-15]. Chapter III discusses this method in detail.

c. *Narrowband Criterion Method*

Since the broadband and the octave band criteria methods lack detailed vibration information, a narrowband criterion method is gaining popularity. The bandwidth may be up to 10% of the center frequency range (typically 10 to 1,000 Hz). The improved resolution is generally up to 400 or 800 lines over the frequency range of interest. With knowledge of the forcing frequencies of rotating components, the narrowband data is very useful for diagnosing specific faults. This diagnosis can be time consuming; it is also often difficult to explain the source of some of the peaks in the spectra.

Frequency criteria are used in U.S. Navy surface ship to establish alarm settings for machinery [Ref. 3]. Vibration data for each individual machine and location are processed to yield mean and standard deviation values from frequency spectra data. Generally, broadband levels are used as a screening tools, and narrowband levels are used as diagnostic tools.

III. METHODS OF ANALYSIS

A. DATA ACQUISITION AND PROCESSING SYSTEM

A block diagram of the data acquisition and analysis system used is depicted in Figure 5. The Model 4800 FM recorder plays back the machinery vibration data tapes to generate an analog signal. By using a connector, this analog signal is distributed to the data acquisition software and the oscilloscope simultaneously. The oscilloscope controls the quality of the data by monitoring the signal time waveform. The EASYEST™ LX software, developed by Keithley Asyst, was used as a data acquisition system. This PC-based data acquisition system allowed us to digitize analog signals, convert the units from voltage to velocity and store the velocity data sequences into the hard disk of a personal computer. Finally, MATLAB software was used to retrieve these data sequences and perform data processing. MATLAB is a very powerful software tool for signal processing. All programs used in this research were written using MATLAB. The synopsis, on-line help documentation and program code used can be found in Appendix A. Examples for the use of these programs to perform the analysis are included in Appendix B.

All of the data sets were sampled at a sampling frequency of 10k Hz. The sampling duration for each data set was 36.684 seconds.

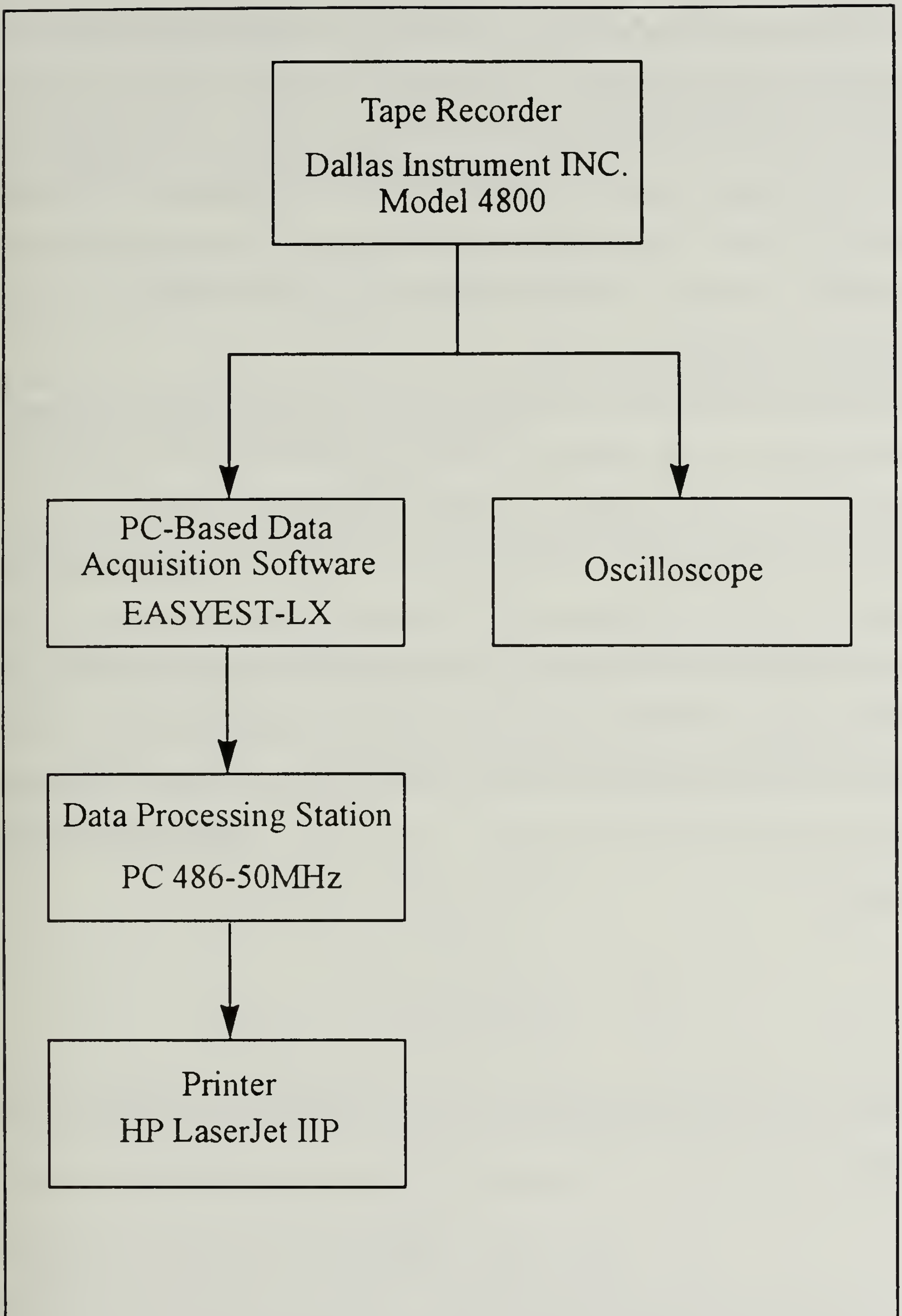


Figure 5 Block Diagram of Data Acquisition And Processing System

B. TIME DOMAIN - CROSS PEAK ANALYSIS

It is obvious that the peak envelope distribution of vibration time domain signals is relevant to the vibration severity of machinery component. Vibration severity criteria which uses measured RMS values to determine the severity of component vibration without considering the dispersion of the signal is truly a rough guess. A better approach is to represent the severity of component vibration in terms of a percentage acceptance level. The percentage acceptance level provides the percentage of outcomes which will not exceed this level threshold.

For a Normal distribution, the acceptance level is closely related to the mean (μ) and standard deviation (σ). For example, $\mu+1.96\sigma$ corresponds to a 97.5% acceptance level which means only a 2.5% probability the signal amplitude will exceed the $\mu+1.96\sigma$ value. For the sake of simplicity, the most popular assumption to assume the probability distribution of the signal was a Gaussian (or Normal) distribution. However, for rotational machinery vibration, since we are only concern with the magnitude of the signal, the probability density function has a skewed rather than a Normal distribution. At this point, it is worthwhile to review the statistical moments and central moments of a random variable [Ref. 16]. For the discrete random variable x with probability $Pr(x)$, the nth moment $E(x^n)$ is defined as:

$$E(x^n) = \sum_{k=1}^{\infty} x_k^n \, Pr(x_k) \qquad (1)$$

The first moment is particularly important in many applications and is given the name mean value (μ):

$$\mu_x = E(x) = \sum_{k=1}^{\infty} x_k \, Pr(x_k) \qquad (2)$$

Of greater significance are the central moments which defined as:

$$E[(x-\mu_x)^n] = \sum_{k=1}^{\infty} (x_k-\mu_x)^n \; Pr(x_k) \qquad (3)$$

The central moment for $n=1$ is zero. The central moment for $n=2$ is a very important which quantity called the variance of the random variable;

$$E[(x-\mu_x)^2] = \sum_{k=1}^{\infty} (x_k-\mu_x)^2 \; Pr(x_k) \qquad (4)$$

The standard deviation, which corresponds to the dispersion of the random variable, can be obtained by taking the square root of the variance,i.e.

$$\sigma = \sqrt{Variance} \qquad (5)$$

As noted earlier, the mean and standard deviation are often used to compute the acceptance level.

The higher order central moments ($n>2$) are often normalized by dividing by the nth power of the standard deviation. The third and fourth normalized central moments are primarily used to indicate the shape of the probability density function. They are defined by the following equations:

$$Skewness = \frac{E[(x-\mu_x)^3]}{\sigma^3} \qquad (6)$$

$$Kurtosis = \frac{E[(x-\mu_x)^4]}{\sigma^4} \qquad (7)$$

The skewness shows information about the position of the peak density relative to the mean value. The kurtosis indicate the spread in the distribution. For a perfect Normal distribution, the skewness is zero and the kurtosis is three.

Since we are interested in the peak envelope distribution of the vibration signal, we use the cross peak data points instead of the overall peak data points. The cross peak technique can extract the dominant component from a complicated time waveform data set by selecting the maximum peak value between every zero crossing. Figure 6 illustrates the difference between overall peak and cross peak points.

As we will see in Chapter IV, the probability distributions of cross peak points have highly positive skewness and can be approximated as a lognormal distribution. This means that the distributions will become normal if the data is transformed by a log or natural log algorithm. The method chosen to accomplish this transformation was to convert the linear velocity reading to velocity dB (VdB) reading. The VdB is defined as:

$$Velocity(VdB) = 20 \log \frac{V}{V_{ref}} \qquad (8)$$

where V_{ref} is the reference level, normally 0VdB=10^{-8} m/sec.

Figure 7 shows a flow chart for our cross peak analysis technique. First, the sampled data is imported into a MATLAB worksheet. The DC offset is then removed by subtracting the mean value of the sampled data. The cross peak points between every zero crossing is then found using a subroutine. As can be seen from Table 1, the dynamic range of the tape recorder is 40 dB. This means that amplitude smaller than 1% of the maximum peak may be distorted. For this reason, we set a 1% threshold to eliminate these distorted points. Equation 8 was then used to transform the linear velocity scale into the VdB domain. The reference 0VdB was 10^{-8} m/sec. After we computed the mean, standard deviation, skewness and kurtosis, plots of the probability density function were generated. Finally, the statistical analysis report can be sent to laser printer.

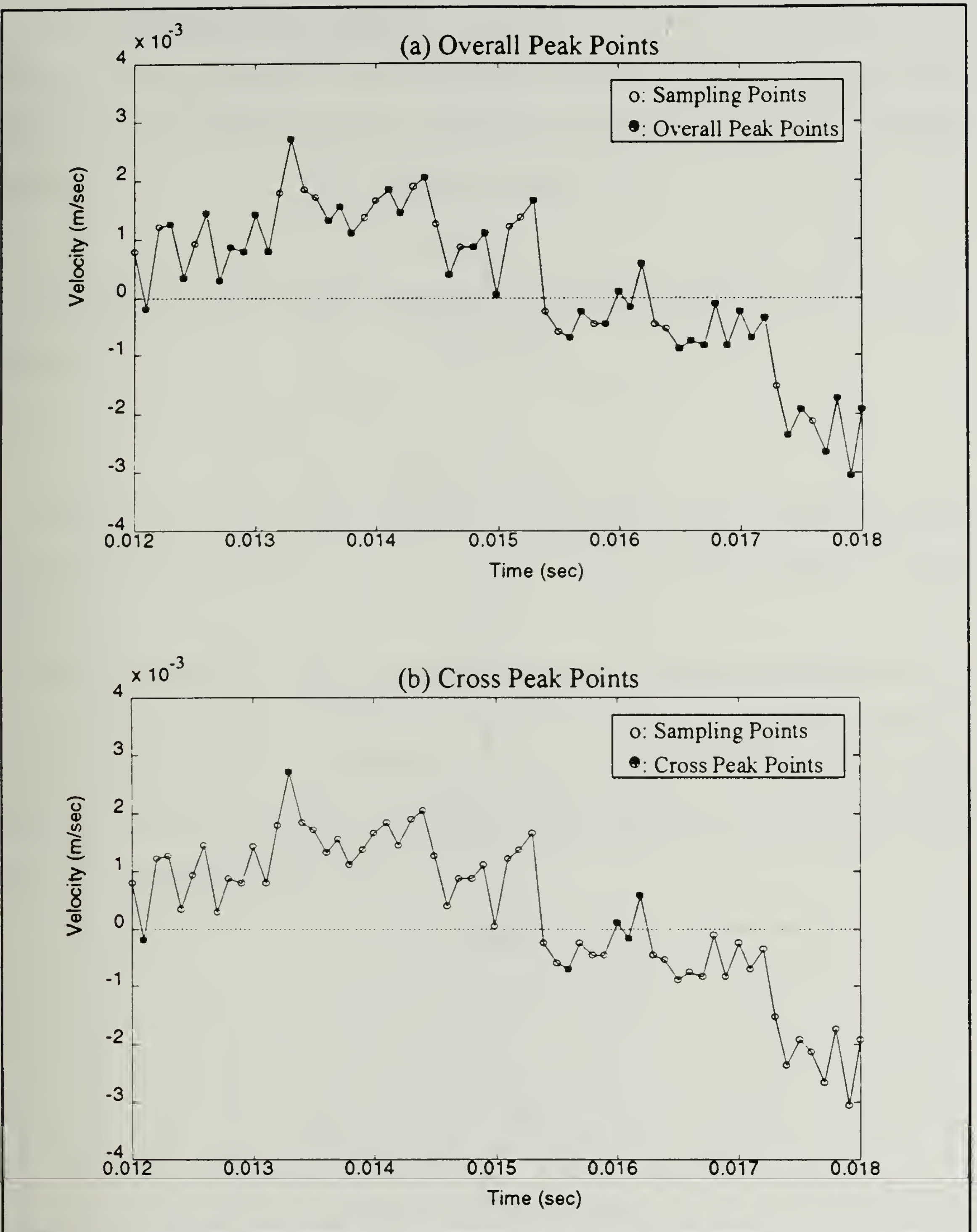


Figure 6 Comparison of Overall Peak and Cross Peak Points (a) Overall Peak Points (b) Cross Peak Points

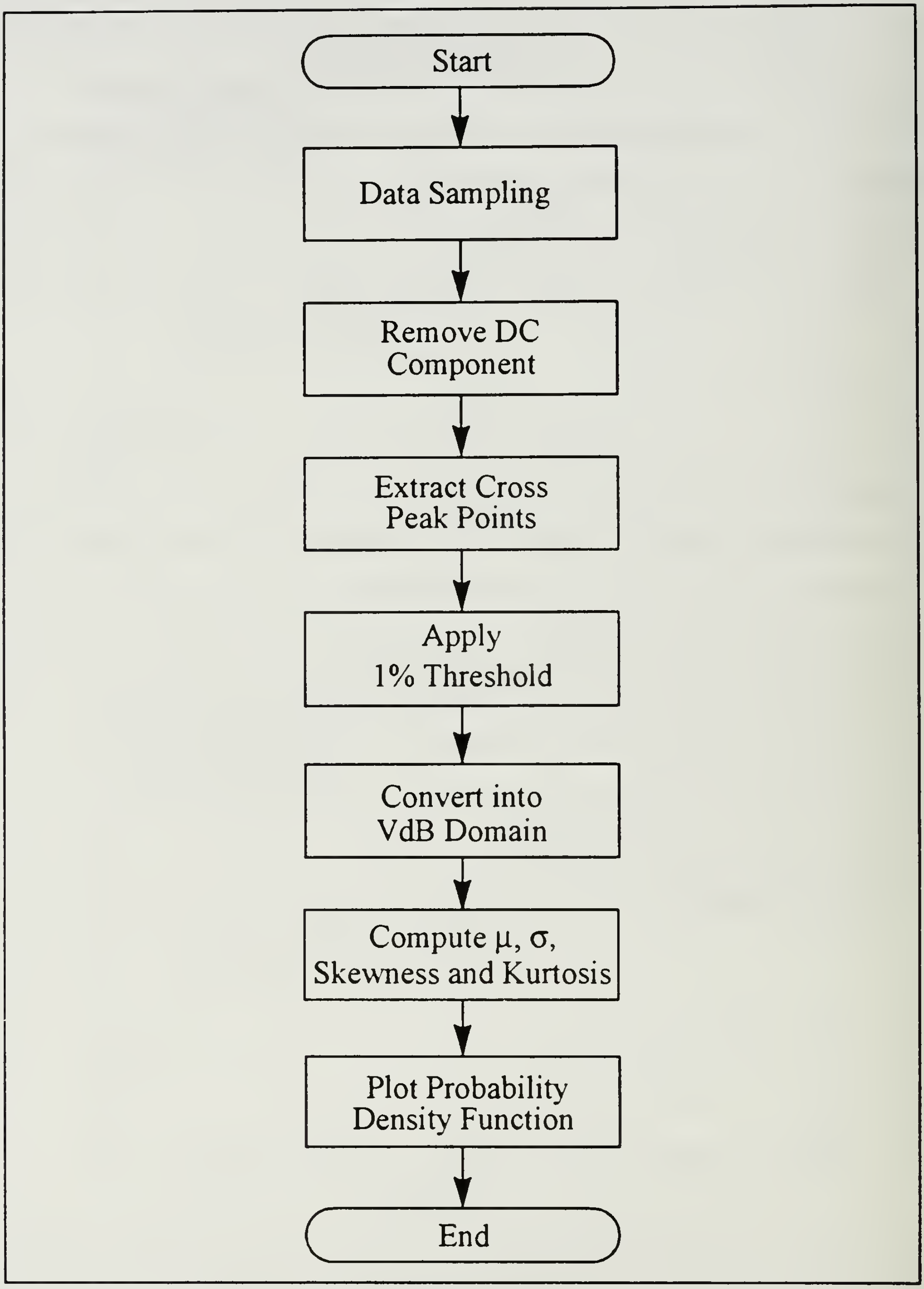


Figure 7 Cross Peak Analysis Flow Chart

C. FREQUENCY DOMAIN - 1/1 OCTAVE BAND ANALYSIS

This method divides the frequency spectrum into constant percentage bands having the same ratio of bandwidth to center frequency [Ref. 17]. Each band has an upper frequency limit (f_2) and lower frequency limit (f_1). The center frequency (f_c) of any band is defined as

$$f_c = \sqrt{f_1 \, f_2} \qquad (9)$$

The ratio of center frequencies of successive proportional bands is the same as f_2/f_1 for any one band. i.e.

$$\frac{f_c}{f_1} = \frac{f_2}{f_c} = \sqrt{\frac{f_2}{f_1}} = 2^{n/2} \qquad (10)$$

One third of an octave is defined as n=1/3. The American National Standards Institute (ANSI) preferred center frequencies and pass bands for 1/3 octave bands is tabulated at Table 7.

The method chosen to examine the frequency domain alarm levels in this research was to use 1/1 octave bands (n=1). For the 10-5,000 Hz frequency range of our system, the frequency spectrum can be divided into 9 bands using the ANSI preferred center frequencies. The center frequencies and pass bands covering the frequency range 10-5,000 Hz in 1/1 octave bands are given in Table 8.

Table 7: ANSI PREFERRED CENTER FREQUENCIES AND PASS BANDS FOR 1/3 OCTAVE BAND

Center Frequency (Hz)	Pass Band (Hz)	
	Lower Limit	Upper Limit
12.5	12	14
16	14	18
20	18	22.4
25	22.4	28
31.5	28	35.5
40	35.5	45
50	45	56
63	56	71
80	71	90
100	90	112
125	112	140
160	140	180
200	180	224
250	224	280
315	280	355
400	355	450
500	450	560
630	560	710
800	710	890
1000	890	1120
1250	1120	1400
1600	1400	1800
2000	1800	2240
2500	2240	2800
3150	2800	3550
4000	3550	4500
5000	4500	5600
6300	5600	7100
8000	7100	9000
10000	9000	11200

Table 8: ANSI PREFERRED CENTER FREQUENCIES AND PASS BANDS FOR 1/1 OCTAVE BAND

Center Frequency (Hz)	Pass Band (Hz)	
	Lower Limit	Upper Limit
16	11.2	22.4
31.5	22.4	45
63	45	90
125	90	180
250	180	355
500	355	710
1000	710	1400
2000	1400	2800
4000	2800	5600
8000	5600	11200

Figure 8 shows the flow chart for our 1/1 octave band analysis using the MATLAB program developed. This technique used frequency domain data to compute the 1/1 octave band levels. In order to have better resolution at lower frequency, it was necessary to use two spectrum data with different sampling frequencies. For the time domain data, the lower sampling frequency spanned 2 kHz and the higher sampling frequency spanned 10 kHz. Twenty blocks of data is sampled at each sampling frequency, a block of data being 2048 data points. After sampling, a FFT was performed for each block with a Hanning window to obtain the smoothed linear velocity spectrum. The averaging VdB spectrum was then produced by transforming the linear spectrum to the VdB domain and taking an average over the 20 data blocks. For the frequency domain data received from the NAVSSES database, 10 order and 100 order data sets were used as the lower frequency spectrum and higher frequency spectrum, respectively. The 1st through 6th 1/1 octave band levels were then computed using the lower frequency sampling spectrum and the 7th through 9th 1/1 octave band levels obtained using the higher frequency sampling spectrum. Finally, the 1/1 octave band analysis was done after combining these two ranges into 9 band levels.

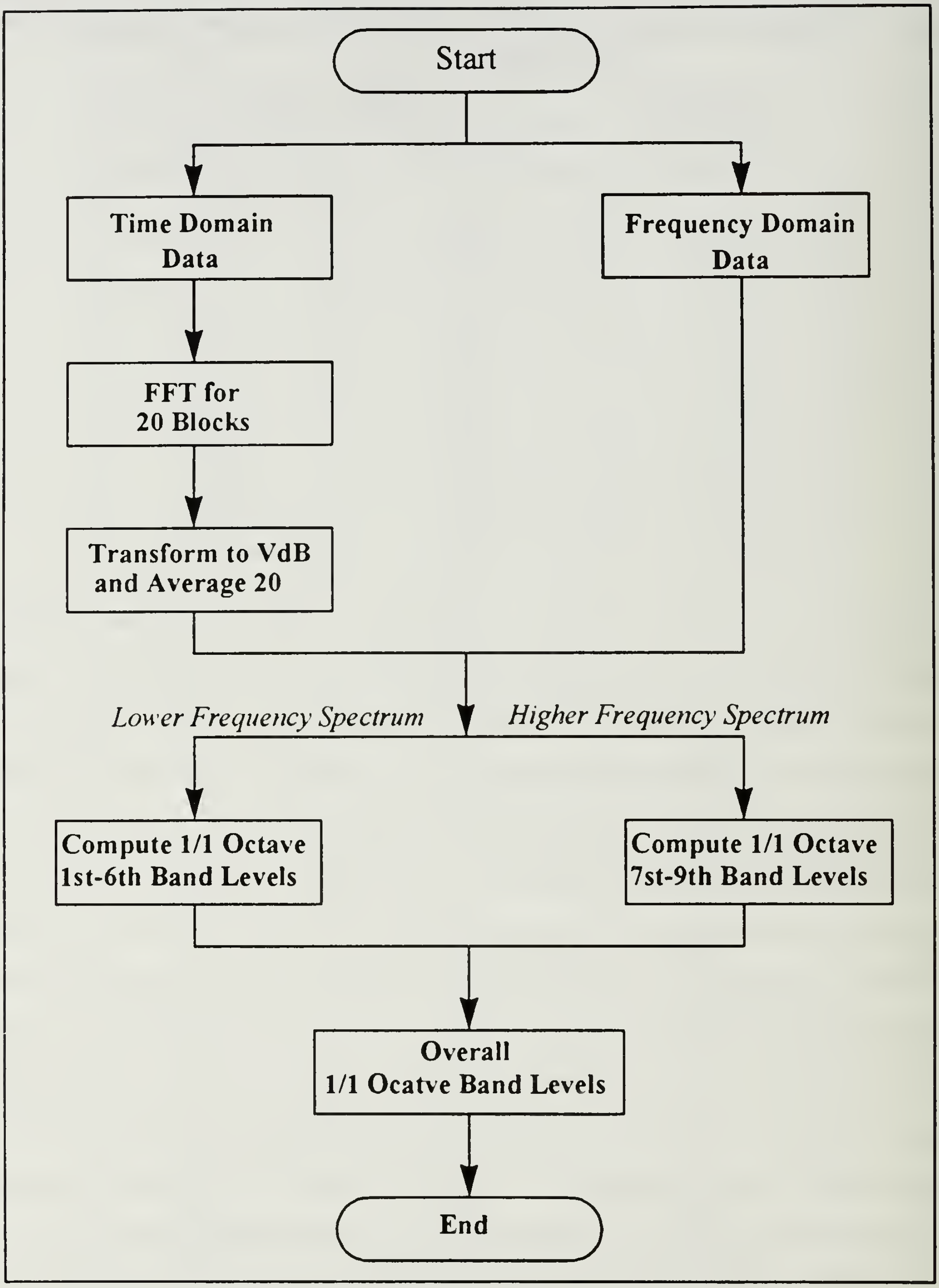


Figure 11 Flow Chart of 1/1 Octave Band Analysis Technique

IV. RESULTS OF USING TIME WAVEFORM TAPES

A. CROSS PEAK ANALYSIS

1. Probability Distribution of Cross Peaks

The available data was digitized and then grouped into three types after examination of the spectrum patterns. Typical time series and frequency spectrums for each type of fire pump are depicted in Figure 9 through Figure 11. The data collection sheets are summarized in Table 9 through Table 13 for each class of ship. One set of data is missing; the actual number of data sets analyzed was 134. The operation speed of the shaft was selected as a reference speed. This speed was used to normalize the frequency scale into "orders". The "B.B. Level" is the broadband level measured by vibrometer when the data was recorded. This level represents the total energy of the velocity reading for each measurement. The full scale represent the calibration factor. The "B.B. Alm Level" is the broadband alarm level set by NAVSSES using the vibrometer reading data. Both the "B.B. Level" and "B.B. Alm Level" was measured for a frequency range from 10 Hz to 10,000 Hz. The remarks column describes the quality of the data set.

In order to understand the distributions of the cross peak points, probability histograms for each set of data were plotted using linear velocity scale. These results are provided in Appendix C. Inspection of these figures shows the distributions to have an exponential shape for the most part. With a linear velocity scale, this type of distribution means that the population is mainly dominated by small peaks which is an expected result for machinery in good condition. Those distributions having a large population at higher amplitudes are regarded as representing damaged pumps. Examination of these damaged data sets shows their broadband levels to be higher than the others and closer to the broadband alarm levels.

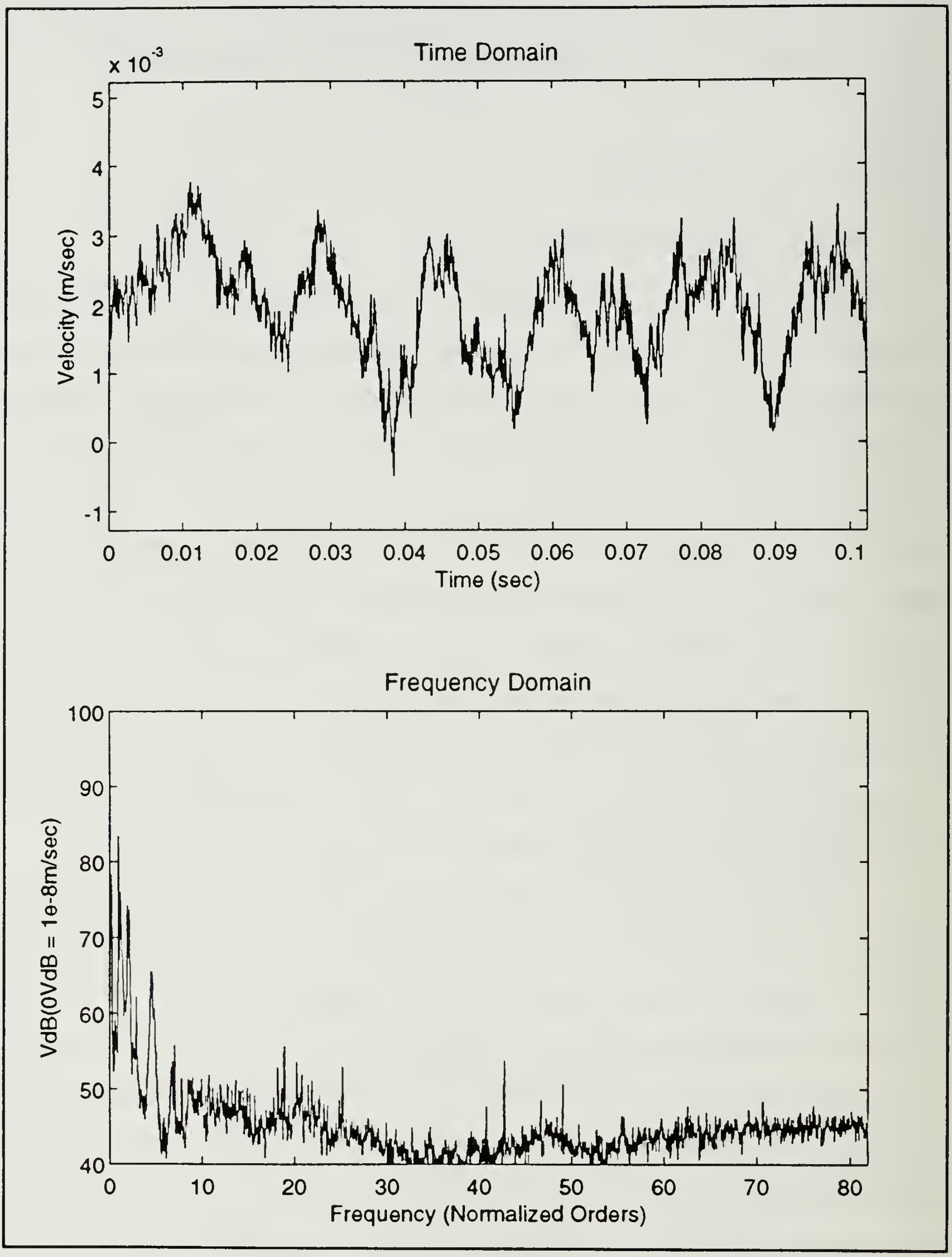


Figure 9 Typical Time Series and Frequency Spectrum of Type I Fire Pumps CG-59(10/30/89) Fire Pump Measured at MB(FE)

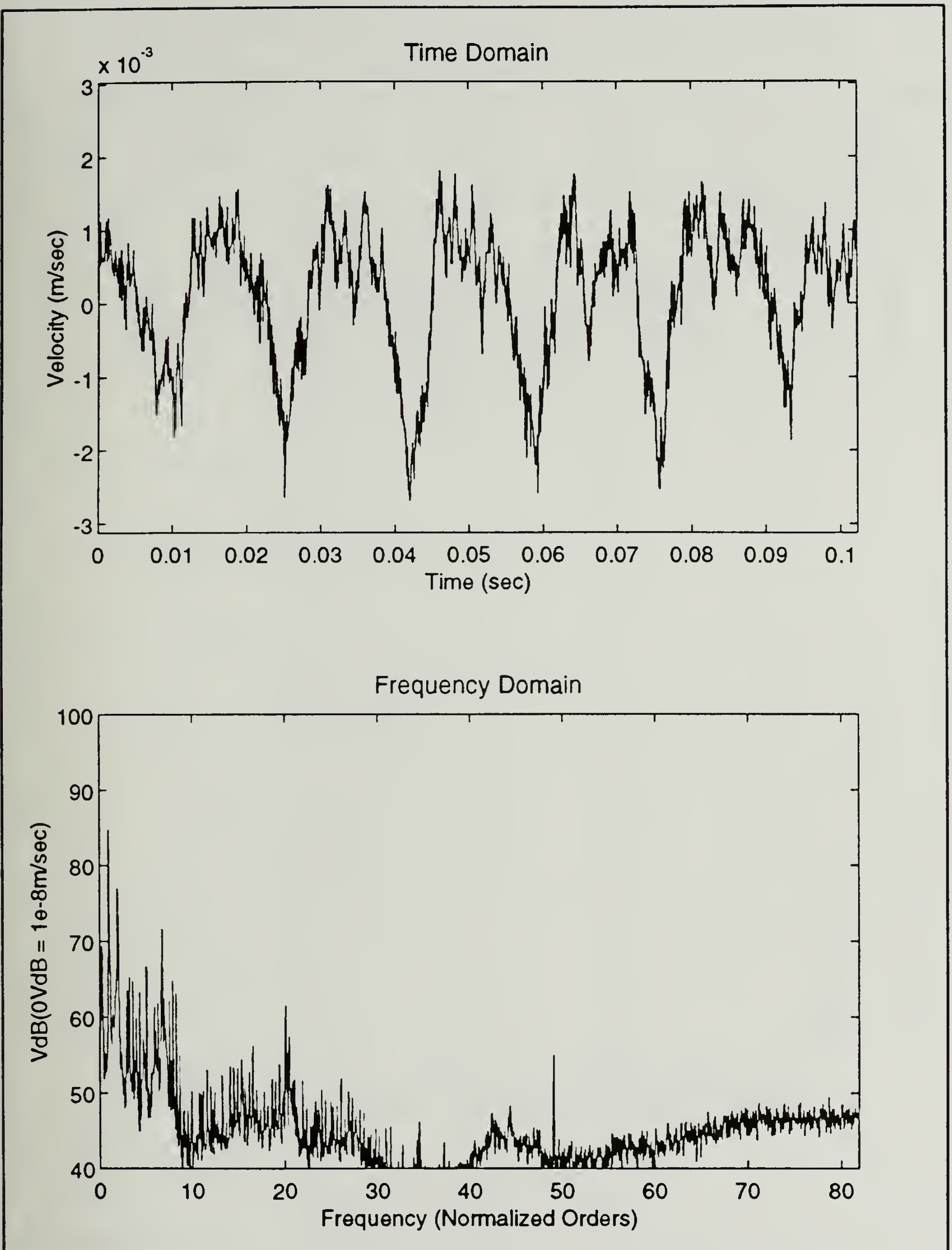


Figure 10 Typical Time Series and Frequency Spectrum of Type II Fire Pumps DDG-994 Fire Pump Measured at MB(FE)

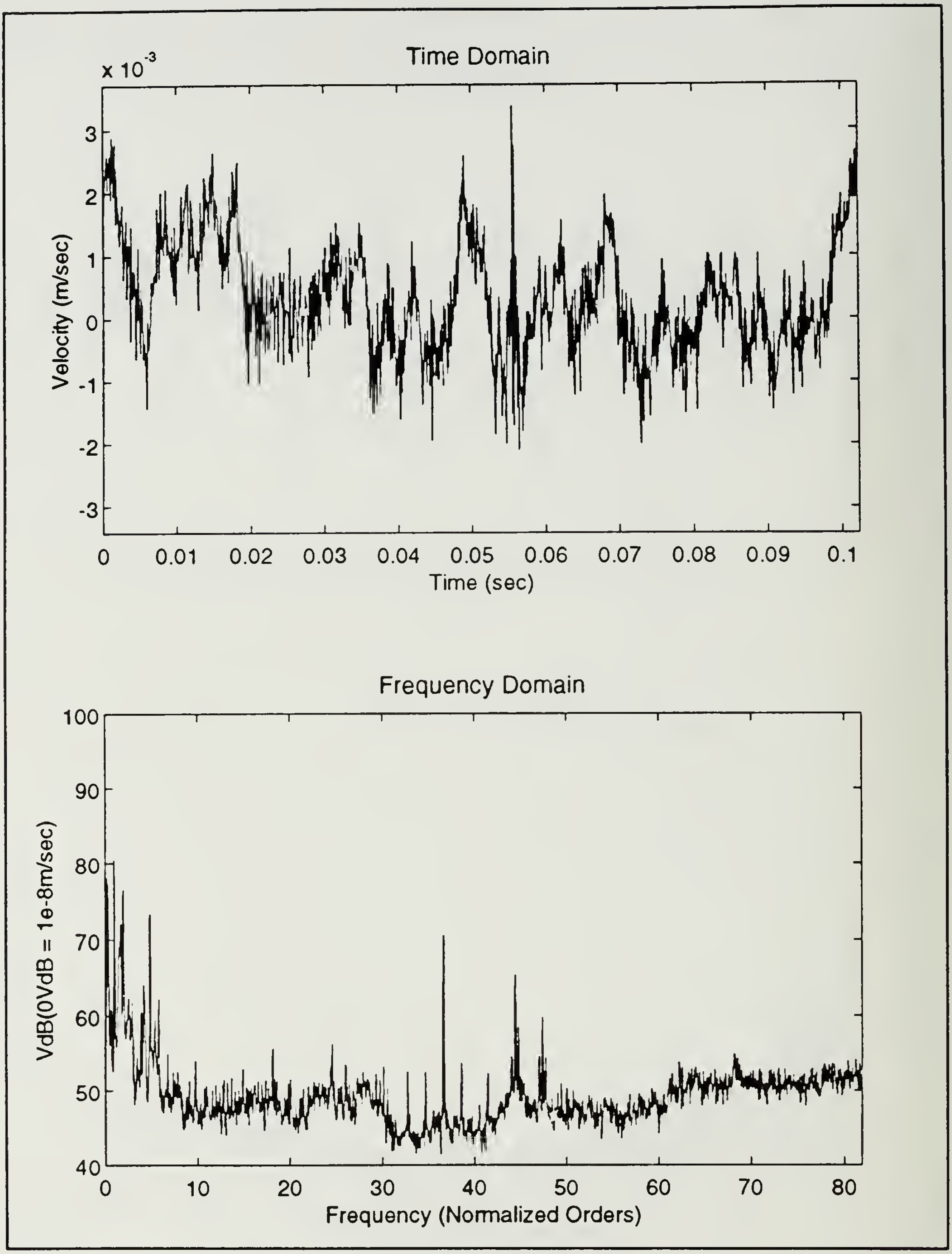


Figure 11 Typical Time Series and Frequency Spectrum of Type III Fire Pumps FF-1071 Fire Pump Measured at UMB

Table 9: DATA COLLECTION SHEET FOR CG-59 (10/30/89)
FIRE PUMP TYPE I

Machine Name	Speed (RPM)	Pickup Location	B.B. Level (VdB)	Full Scale (VdB)	B.B. Alm Level (VdB)	Remarks
Fire Pump #1	3595	MB(FE)	99	120	107	
		MB(CE)	102	120	109	
		PB(CE)	110	120	118	
		PB(FE)	111	120	119	
		PB(FE/A)	114	120	121	
Fire Pump #2	3595	MB(FE)	97	100	107	
		MB(CE)	101	120	109	
		PB(CE)	108	120	118	
		PB(FE)	106	120	119	
		PB(FE/A)	107	120	121	
Fire Pump #3	3595	MB(FE)	97	100	107	
		MB(CE)	100	120	109	
		PB(CE)	111	120	118	
		PB(FE)	109	120	119	
		PB(FE/A)	113	120	121	
Fire Pump #4	3595	MB(FE)	100	120	107	
		MB(CE)	100	120	109	
		PB(CE)	108	120	118	
		PB(FE)	110	120	119	
		PB(FE/A)	111	120	121	
Fire Pump #5	3595	MB(FE)	100	120	107	
		MB(CE)	101	120	109	
		PB(CE)	110	120	118	
		PB(FE)	111	120	119	
		PB(FE/A)	114	120	121	
Fire Pump #6	3595	MB(FE)	99	120	107	
		MB(CE)	100	120	109	
		PB(CE)	113	120	118	Damaged
		PB(FE)	111	120	119	
		PB(FE/A)	111	120	121	

Table 10: DATA COLLECTION SHEET FOR CG-59 (2/26/90)
FIRE PUMP TYPE I

Machine Name	Speed (RPM)	Pickup Location	B.B. Level (VdB)	Full Scale (VdB)	BB Alm Level (VdB)	Remarks
Fire Pump #1	3595	MB(FE)	98	100	107	
		MB(CE)	97	100	109	
		PB(CE)	106	120	118	
		PB(FE)	110	120	119	
		PB(FE/A)	111	120	121	
Fire Pump #2	3595	MB(FE)	97	120	107	
		MB(CE)	96	120	109	
		PB(CE)	108	120	118	
		PB(FE)	107	120	119	
		PB(FE/A)	108	120	121	
Fire Pump #3	3595	MB(FE)	99	120	107	
		MB(CE)	100	120	109	
		PB(CE)	116	120	118	Damaged
		PB(FE)	115	120	119	Damaged
		PB(FE/A)	117	120	121	
Fire Pump #4	3595	MB(FE)	98	120	107	
		MB(CE)	97	120	109	
		PB(CE)	108	120	118	
		PB(FE)	111	120	119	
		PB(FE/A)	112	120	121	
Fire Pump #5	3595	MB(FE)	99	120	107	
		MB(CE)	101	120	109	
		PB(CE)	109	120	118	
		PB(FE)	110	120	119	
		PB(FE/A)	113	120	121	
Fire Pump #6	3595	MB(FE)	99	120	107	
		MB(CE)	98	120	109	
		PB(CE)	115	120	118	Damaged
		PB(FE)	112	120	119	
		PB(FE/A)	113	120	121	

Table 11: DATA COLLECTION SHEET FOR DDG-993
FIRE PUMP TYPE II

Machine Name	Speed (RPM)	Pickup Location	B.B. Level (VdB)	Full Scale (VdB)	BB Alm Level (VdB)	Remarks
Fire Pump #1	3555	MB(FE)	97	120	108	
		MB(CE)	99	120	112	Bad Data
		MB(CE/A)	110	120	112	
		PB(CE)	110	120	117	
		PB(FE)	109	120	119	
Fire Pump #2	3555	MB(FE)	91	100	108	
		MB(CE)	99	120	112	
		MB(CE/A)	107	120	112	
		PB(CE)	108	120	117	
		PB(FE)	109	120	119	
Fire Pump #3	3555	MB(FE)	102	120	108	
		MB(CE)	103	120	112	
		MB(CE/A)	112	120	112	
		PB(CE)	113	120	117	
		PB(FE)	116	120	119	

Table 12: DATA COLLECTION SHEET FOR FF-1062 (11/24/89)
FIRE PUMP TYPE III

Machine Name	Speed (RPM)	Pickup Location	B.B. Level (VdB)	Full Scale (VdB)	BB Alm Level (VdB)	Remarks
Fire Pump #1	3570	UMB	110	120	108	Damaged
		LMB	111	120	110	Damaged
		LMB(A)	103	120	108	
		UPB	117	120	120	Damaged
		LPB	112	120	121	
Fire Pump #2	3570	UMB	97	120	108	
		LMB	98	120	110	
		LMB(A)	98	120	108	
		UPB	107	120	120	
		LPB	105	120	121	
Fire Pump #3	3570	UMB	101	120	108	
		LMB	104	120	110	
		LMB(A)	101	120	108	
		UPB	109	120	120	
		LPB	111	120	121	
Fire Pump #4	3570	UMB	98	120	108	
		LMB	103	120	110	
		LMB(A)	98	120	108	
		UPB	114	120	120	
		LPB	113	120	121	

Table 13: DATA COLLECTION SHEET FOR FF-1071 (3/10/89)
FIRE PUMP TYPE III

Machine Name	Speed (RPM)	Pickup Location	B.B. Level (VdB)	Full Scale (VdB)	BB Alm Level (VdB)	Remarks
Fire Pump #1	3570	UMB	98	120	108	
		LMB	99	120	110	
		LMB(A)	97	120	108	
		UPB	110	120	120	
		LPB	106	120	121	
Fire Pump #2	3570	UMB	96	120	108	
		LMB	104	120	110	Missing
		LMB(A)	102	120	108	
		UPB	117	140	120	
		LPB	114	140	121	
Fire Pump #3	3570	UMB	105	120	108	
		LMB	102	120	110	
		LMB(A)	101	120	108	
		UPB	111	120	120	
		LPB	107	120	121	
Fire Pump #4	3570	UMB	96	100	108	
		LMB	102	120	110	
		LMB(A)	99	120	108	
		UPB	114	120	120	
		LPB	109	120	121	

2. Statistical Analysis Results

As mentioned before, the distributions of the cross peak points in a linear velocity scale have an exponential shape histogram. This shape histogram can be approximated as a lognormal distribution. Because a velocity decibel is a unit of measurement equal to the logarithm of the ratio V/V_{ref}, it is convenient to use the VdB transformation to convert an exponential shaped distribution into a Normal distribution. Before we applied this transform, the 1% threshold was used to remove distorted data. The data sets with same type of fire pump and same pickup location were then added together to form a combined data set to perform the statistical analysis. The results are collected in Appendix D. Figure D.1 through Figure D.15 present the statistical analysis results for all of the available data. Figure D.16 through Figure D.21 show the statistical analysis results without including the damaged data sets. Table 14 tabulates these results in the linear velocity and VdB domains. A comparison of alarm thresholds between the broadband alarm levels (B.B. Alm. Level) and the computed $\mu+2\sigma$ level is shown in Table 15. It should be mentioned that these two alarm thresholds are based on different methods using data from different domains. The broadband alarm level, as noted earlier, is obtained by using vibrometer readings in the frequency domain. The computed $\mu+\sigma$ levels represent the 97.5% acceptance level of the cross peak envelopes in the VdB domain. Several observations can be made:

• The distribution of the cross peak points in the linear velocity domain have a highly positive skew. This can be treated as a lognormal distribution.

• By using the Vdb transformation, the distributions in the linear velocity domain can be transformed to Normal or near Normal distributions Generally speaking, the data sets at pickup locations for the motor have a skewness less than 0.1 and the data sets at pickup locations for the pump ends have a skewness varying between 0.1 and 0.5.

• As can be seen from Table 14, removing the damaged data sets does not cause the probability distributions in the Vdb domain to become much closer to Normal as measured by the skewness and kurtosis. For the MB(CE) pickup location of a type II pump, not considering the damaged pump data sets makes the skewness even more severe than when the damaged pump data sets are considered. Since there were only 3 type II pumps, this result is not surprising.

• In general, the B.B. Alarm Levels and computed $\mu+2\sigma$ levels in the VdB domain are quite close. The relative errors between these two methods for Type I fire pumps are less than 5%. It is also noted from Table 15 that the computed $\mu+2\sigma$ levels in cases with small skewness is closer to the broadband alarm levels than in cases with high skewness. This is because the computed $\mu+2\sigma$ levels for the Normal distribution is very sensitive to skewness.

Table 14: STATISTICAL ANALYSIS RESULTS FOR CROSS PEAK POINTS

Type	Pickup Position	Linear Velocity Domain				VdB Domain			
		μ (mm/s)	σ (mm/s)	Skew.	Kurt.	μ (VdB)	σ (VdB)	Skew.	Kurt.
I	MB(FE)	0.495	0.533	1.850	6.201	89.36	9.20	-0.046	2.378
	MB(CE)	0.539	0.608	2.052	7.195	90.20	9.12	0.049	2.444
	PB(CE)	2.828	2.680	1.517	5.638	104.6	9.78	-0.444	2.476
	PB(FE)	2.717	2.681	1.253	3.959	103.6	10.45	-0.335	2.232
	PB(FE/A)	3.699	3.307	1.086	3.515	106.9	9.90	-0.519	2.472
	PB(CE)*	2.319	1.988	1.046	3.304	103.3	9.25	-0.510	2.506
	PB(FE)*	2.525	2.472	1.169	3.409	103.0	10.30	-0.317	2.228
II	MB(FE)	0.504	0.604	2.059	6.976	88.4	10.50	-0.139	2.420
	MB(CE)	0.727	0.763	3.243	66.02	93.1	8.78	-0.022	2.320
	MB(CE/A)	2.148	2.493	1.321	3.604	100.0	11.49	0.019	1.926
	PB(CE)	2.484	2.344	0.905	2.675	102.6	10.84	-0.368	2.038
	PB(FE)	2.166	2.739	2.008	6.446	100.8	10.29	0.113	2.366
	MB(CE)*	0.619	0.811	2.146	6.762	90.5	9.19	0.495	2.566
III	UMB	0.672	0.926	4.985	36.52	92.1	8.69	0.029	2.953
	LMB	0.923	1.046	3.350	19.59	95.3	8.56	-0.077	2.697
	LMB(A)	0.703	0.648	1.881	7.538	93.3	8.46	-0.349	2.663
	UPB	4.141	4.442	1.570	5.446	106.1	11.84	-0.408	2.207
	LPB	3.160	3.246	1.779	6.775	105.1	10.20	-0.373	2.430
	UMB*	0.597	0.602	2.488	11.46	91.8	8.34	-0.167	2.595
	LMB*	0.776	0.736	1.980	7.430	94.3	8.15	-0.181	2.555
	UPB*	3.603	3.906	1.711	6.361	105.1	11.60	-0.367	2.176

* : The statistical analysis results without considering the damaged data sets.

Table 15: COMPARISOM OF COMPUTED $\mu+2\sigma$ LEVEL AND BROADBAND ALARM LEVEL

Type	Pickup Position	Skewness	μ (VdB)	σ (VdB)	$\mu+2\sigma$ (VdB)	B.B.Alarm Level (VdB)	Relative Error
I	MB(FE)	-0.046	89.36	9.20	107.8	107	0.71%
	MB(CE)	0.049	90.20	9.12	108.3	109	-0.68%
	PB(CE)	-0.444	104.6	9.78	124.2	118	4.95%
	PB(FE)	-0.335	103.6	10.45	124.5	119	4.42%
	PB(FE/A)	-0.519	106.9	9.90	126.7	121	4.50%
	PB(CE)*	-0.510	103.3	9.25	121.8	118	3.11%
	PB(FE)*	-0.317	103.0	10.30	123.6	119	3.72%
II	MB(FE)	-0.139	88.4	10.50	109.4	108	1.27%
	MB(CE)	-0.022	93.1	8.78	110.6	112	-1.25%
	MB(CE/A)	0.019	100.0	11.49	123.0	112	8.91%
	PB(CE)	-0.368	102.6	10.84	124.3	117	5.86%
	PB(FE)	0.113	100.8	10.29	121.4	119	1.96%
	MB(CE)*	0.495	90.5	9.19	108.9	118	-8.37%
III	UMB	0.029	92.1	8.69	109.5	108	1.40%
	LMB	-0.077	95.3	8.56	112.4	110	2.11%
	LMB(A)	-0.349	93.3	8.46	110.2	108	2.04%
	UPB	-0.408	106.1	11.84	129.8	120	7.54%
	LPB	-0.373	105.1	10.20	125.5	121	3.59%
	UMB*	-0.167	91.8	8.34	108.5	108	0.44%
	LMB*	-0.181	94.3	8.15	110.6	110	0.52%
	UPB*	-0.367	105.1	11.60	128.3	120	6.47%

* : The statistical analysis results without considering the damaged data sets.

B. 1/1 OCTAVE BAND ANALYSIS

1. 1/1 Octave Band Analysis Results

The 1/1 octave band analysis was performed for all types of fire pumps with the time domain data. Band 1 through band 6 were computed by using f_s=2 kHz to provide better resolution at lower frequencies. Band 7 to band 9 were computed by using f_s=10 kHz. Appendix E contains figures for all of the 1/1 octave band levels for each set of data. The 10-5,000 Hz broadband levels are also shown on these plots. It was computed by adding all the VdB spectrum using a RMS algorithm. The means (μ) and standard deviations (σ) of each octave band levels for the same type fire pumps with the same pickup locations was also computed. Figure 12 through Figure 14 show the summarized 1/1 octave band levels for each type of fire pump without considering the damaged data sets. The thin line represents the mean (μ) band level and the thick line represents the mean plus one standard deviation ($\mu+\sigma$) band level. Table 16 tabulates these band levels.

Generally speaking, the dominate levels are located in the first six bands (10 to 710 Hz). This implies that the energy of vibration is concentrated at lower frequencies. For fire pumps with a 3555 RPM operation speed, these bands are approximated up to 12 orders. Upon examination of the third band through the sixth band for each data set, it is obvious that the band levels for damaged data sets are higher than the for undamaged pump data sets.

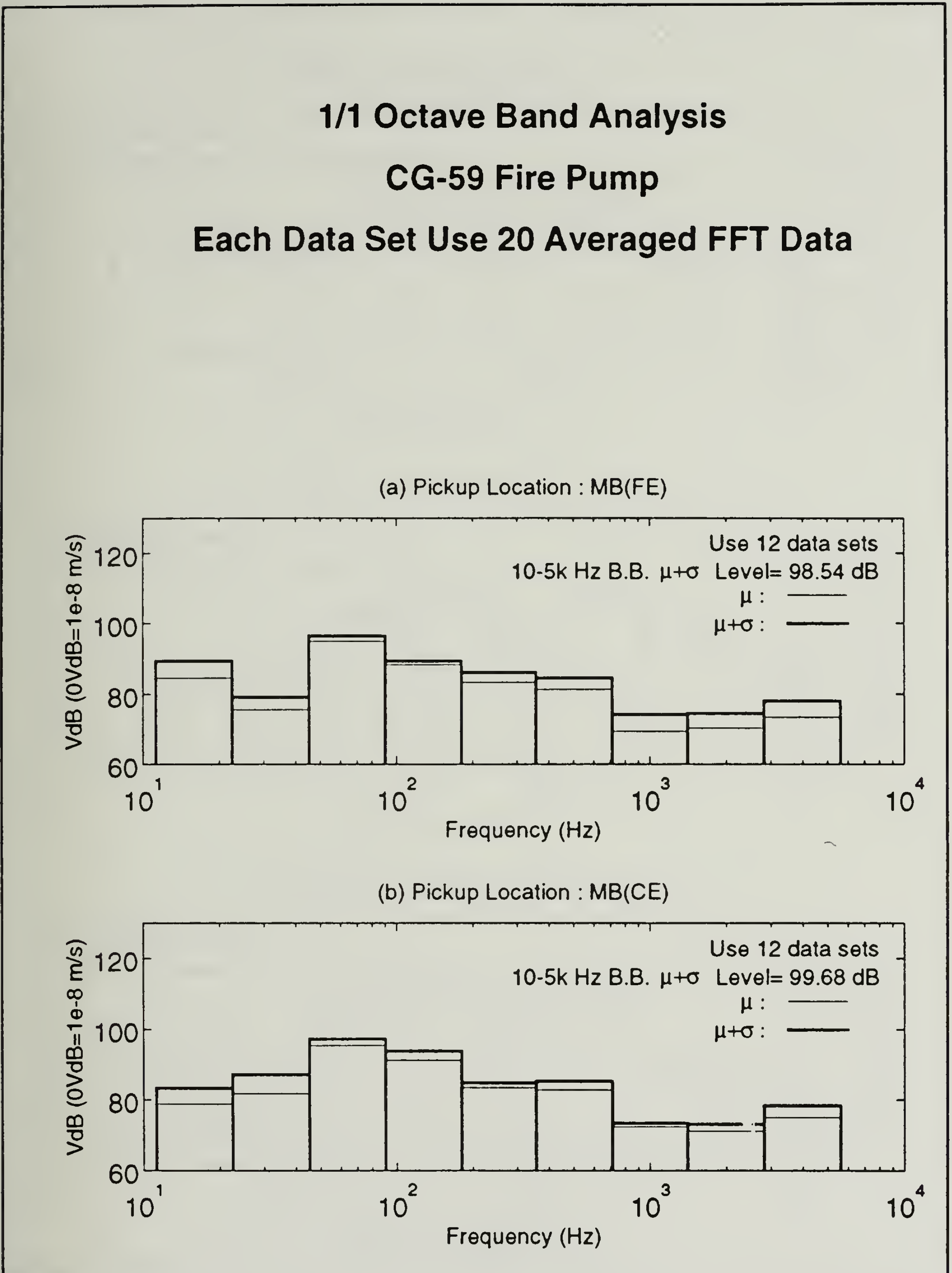


Figure 12 The Summarized 1/1 Octave Band Levels for Type I Fire Pumps

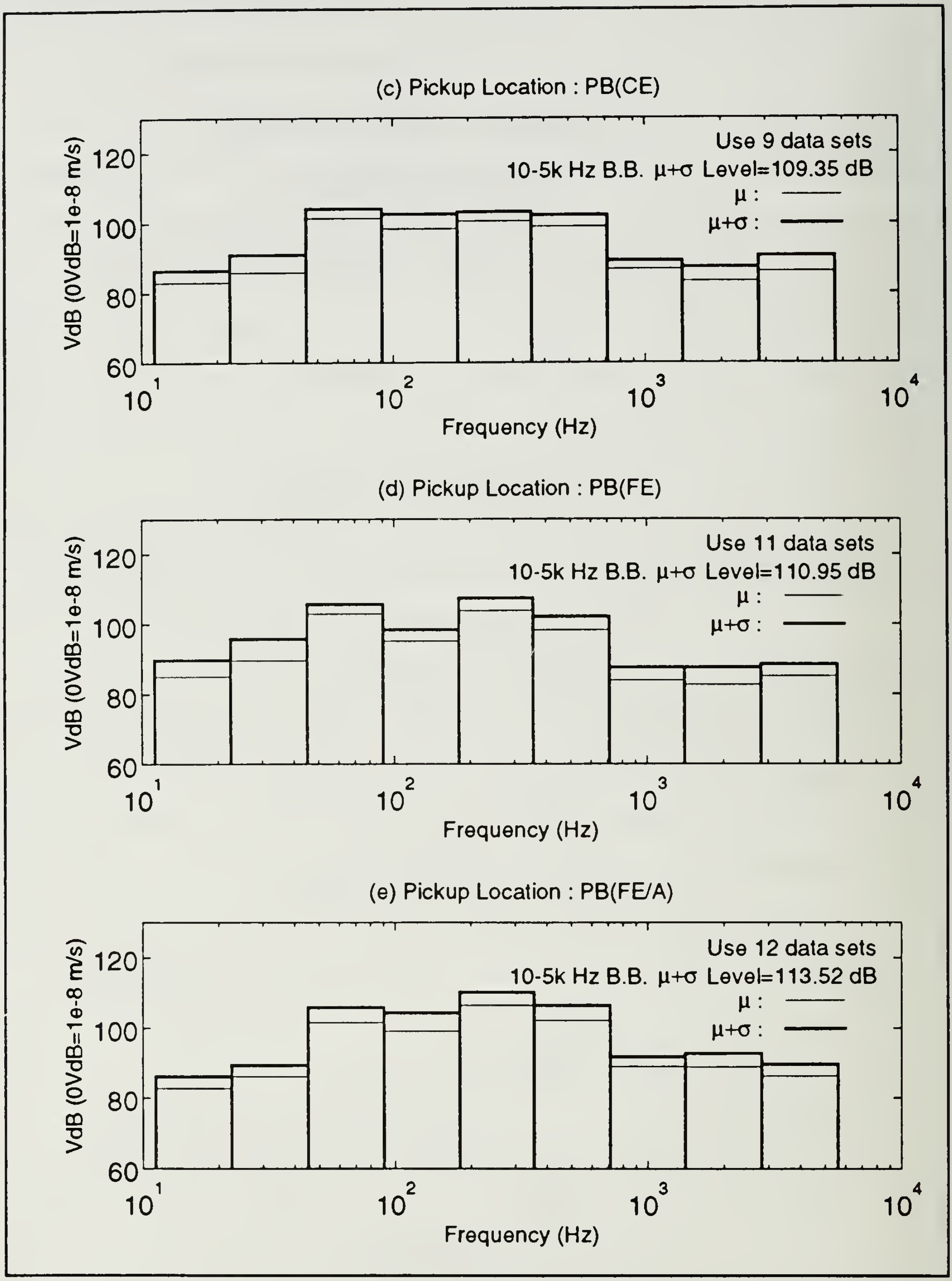


Figure 12 The Summarized 1/1 Octave Band Levels for Type I Fire Pumps (Cont.)

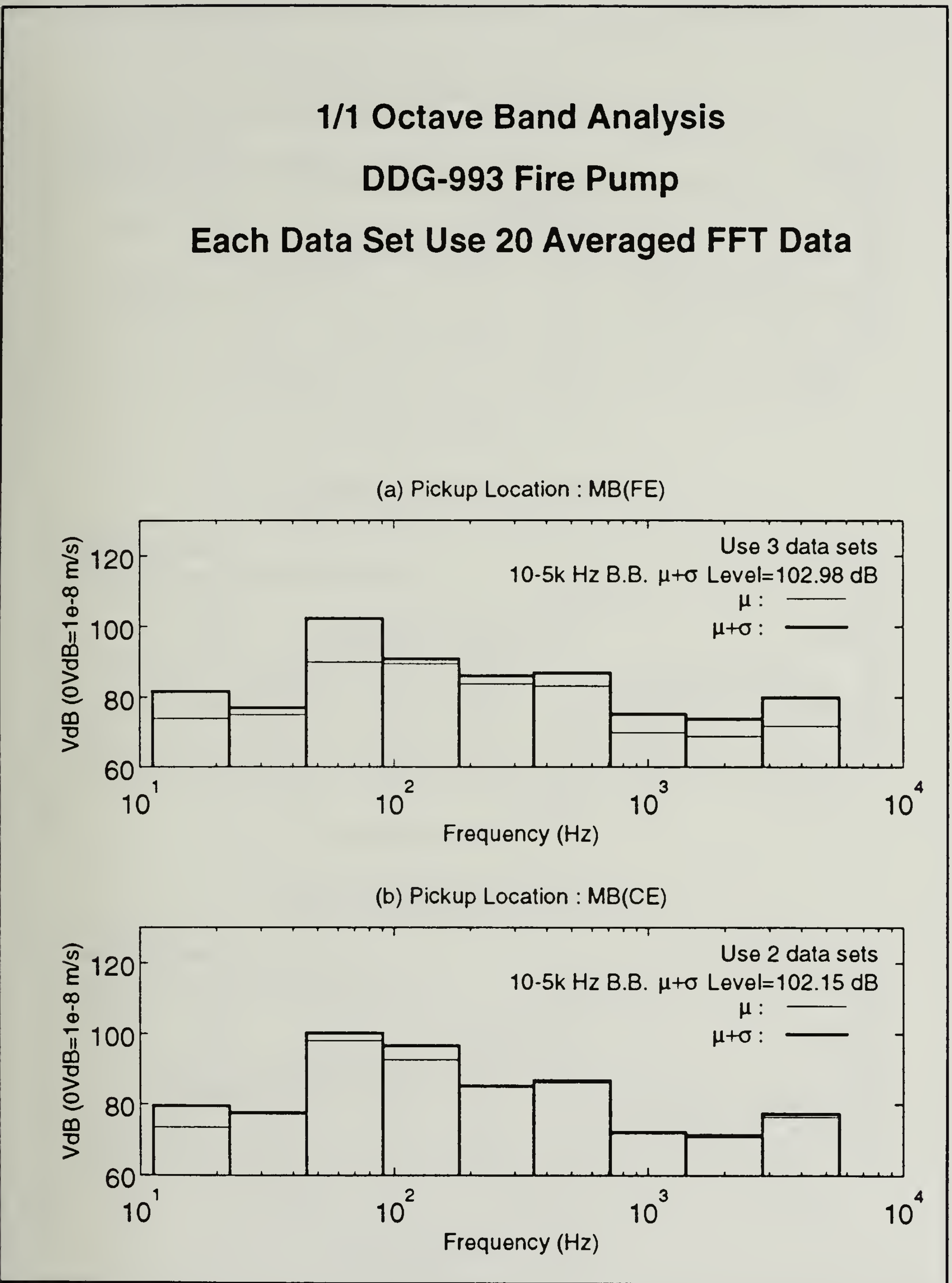


Figure 13 The Summarized 1/1 Octave Band Levels for Type II Fire Pumps

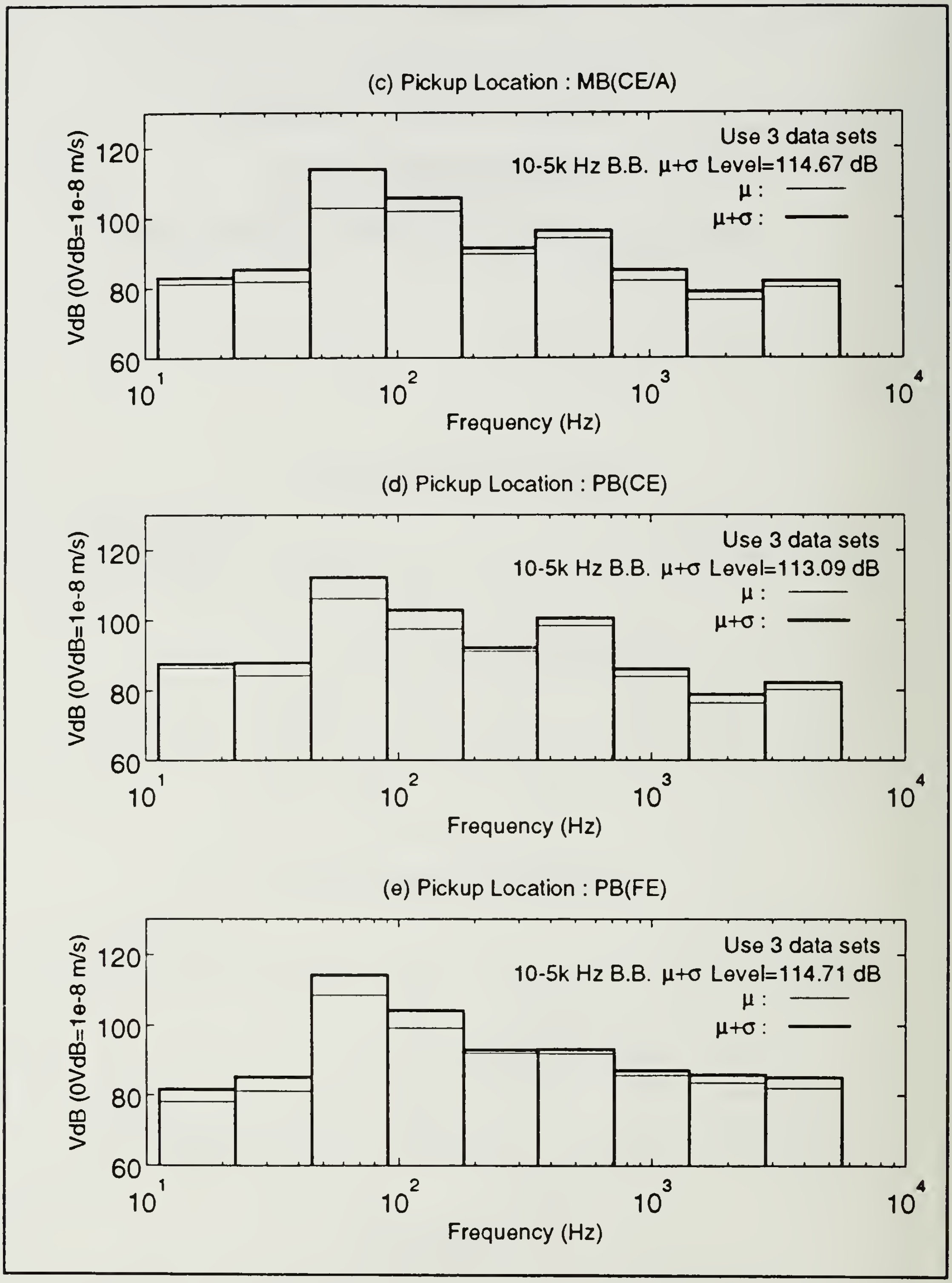


Figure 13 The Summarized 1/1 Octave Band Levels for Type II Fire Pumps (Cont.)

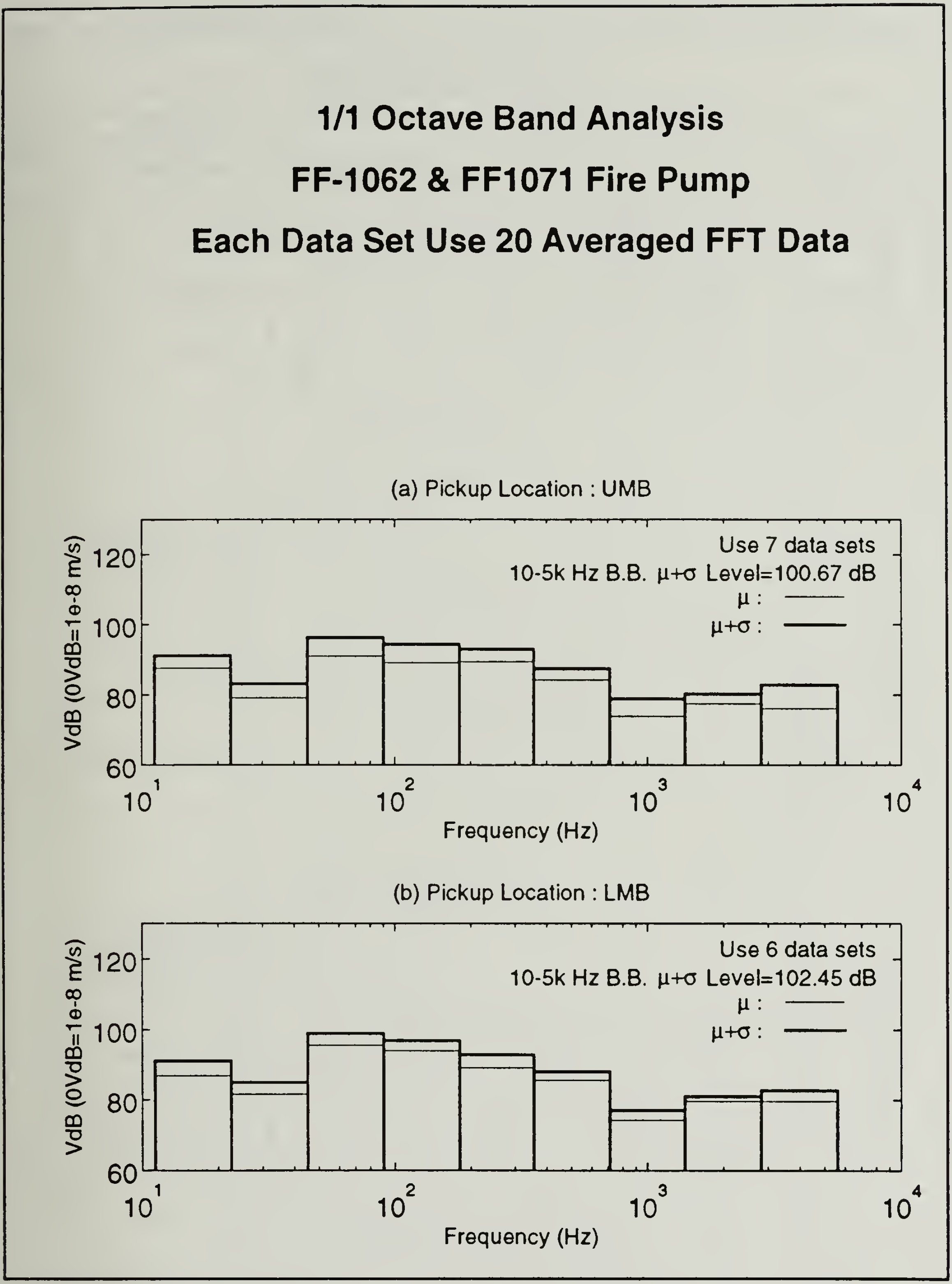


Figure 14 The Summarized 1/1 Octave Band Levels for Type III Fire Pumps

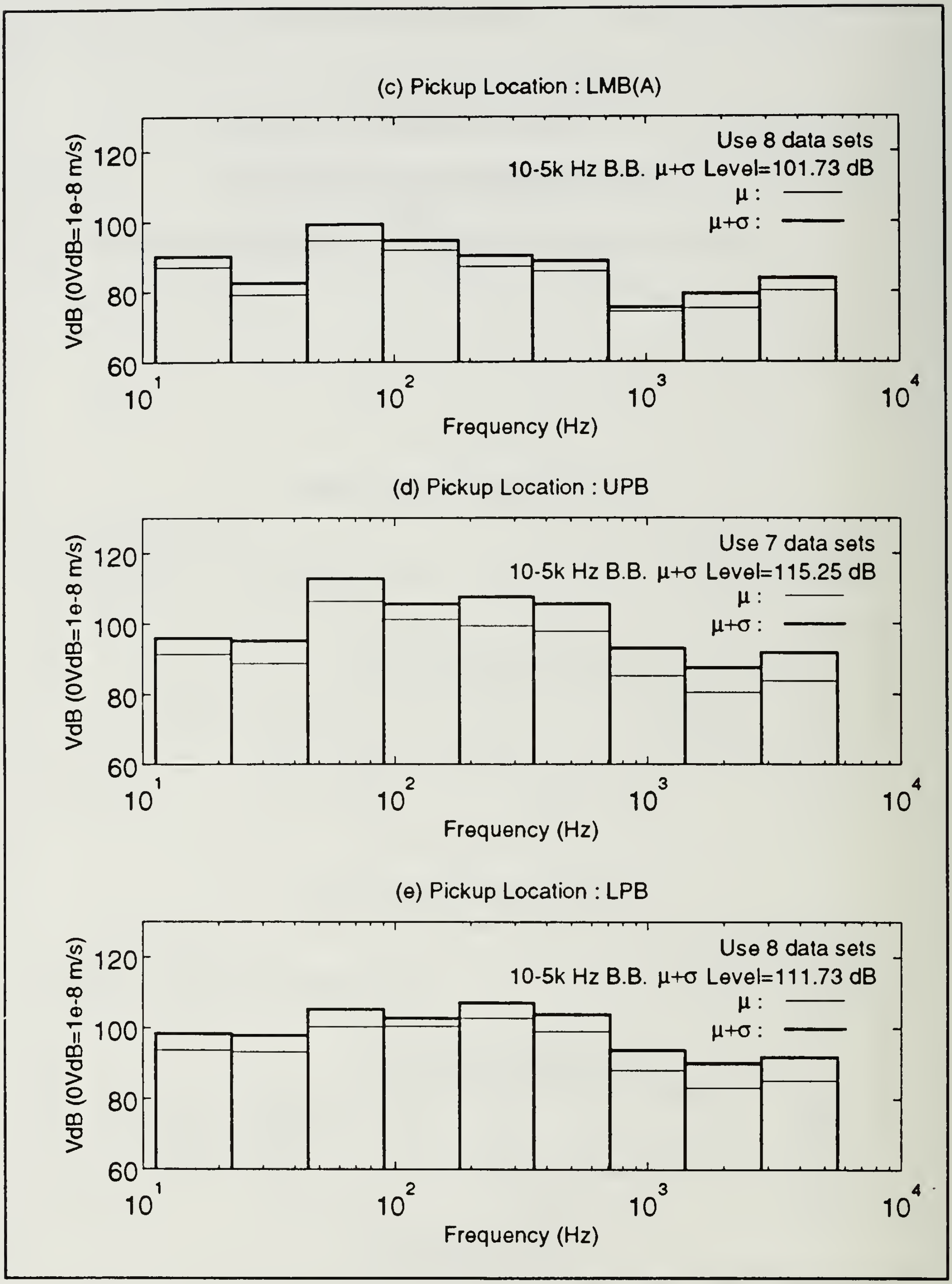


Figure 14 The Summarized 1/1 Octave Band Levels for Type III Fire Pumps (Cont.)

Table 16: SUMMARIZED MEAN (μ) AND STANDARD DEVIATION (σ) OF 1/1 OCTAVE BAND LEVELS

Type	Pickup Location		Band Level (VdB) 0VdB=1e-8 m/sec								
			1st	2nd	3rd	4th	5th	6th	7th	8th	9th
I	MB(FE)	μ	84.5	75.5	95.0	88.3	83.4	81.3	69.4	70.3	73.4
		σ	4.87	3.59	1.56	1.09	2.72	3.34	4.84	4.16	4.70
	MB(CE)	μ	78.9	81.8	95.5	91.3	83.6	83.0	72.5	71.2	75.1
		σ	4.48	5.49	1.79	2.54	1.34	2.42	1.09	1.95	3.45
	PB(CE)	μ	83.2	85.9	101.3	98.4	100.5	99.0	86.8	83.4	86.2
		σ	3.42	5.05	2.90	4.12	2.68	3.29	2.54	4.11	4.56
	PB(FE)	μ	85.0	89.7	102.9	95.3	103.9	98.3	84.0	82.7	85.3
		σ	4.76	6.14	2.90	3.17	3.60	3.96	3.71	4.89	3.38
	PB(FE/A)	μ	82.8	86.3	101.6	99.1	106.6	102.3	89.2	88.9	86.3
		σ	3.41	3.21	4.41	5.30	3.65	4.29	2.67	3.86	3.48
II	MB(FE)	μ	74.0	75.0	90.0	89.5	83.7	83.2	69.8	68.8	71.7
		σ	7.67	1.99	12.44	1.37	2.39	3.73	5.28	4.93	8.23
	MB(CE)	μ	73.6	77.3	98.1	92.8	85.2	86.2	72.2	70.8	76.5
		σ	6.03	0.48	2.14	4.01	0.12	0.60	0.05	0.57	0.94
	MB(CE/A)	μ	81.3	81.9	102.9	102.0	89.8	94.2	82.0	76.6	80.2
		σ	1.86	3.44	11.06	3.87	1.71	2.09	3.09	2.38	1.72
	PB(CE)	μ	86.4	84.3	106.3	97.6	91.2	98.4	83.9	76.3	80.3
		σ	1.36	3.72	6.00	5.37	1.18	2.19	2.19	2.59	1.93
	PB(FE)	μ	78.2	81.2	108.6	99.3	92.3	92.0	85.9	83.7	82.1
		σ	3.55	4.13	5.57	4.88	0.95	1.26	1.38	2.35	3.18
III	UMB	μ	87.6	79.1	91.1	89.2	89.4	84.3	73.9	77.4	76.1
		σ	3.67	3.99	5.29	5.21	3.70	3.22	4.96	2.75	6.76
	LMB	μ	87.0	81.7	95.6	94.0	89.3	85.7	74.3	79.7	79.7
		σ	4.19	3.38	3.42	2.95	3.72	2.49	2.79	1.46	3.18
	LMB(A)	μ	87.1	79.3	94.7	91.9	87.2	85.9	74.4	75.3	80.4
		σ	3.19	3.35	4.57	2.71	3.20	2.93	1.21	4.06	3.57
	UPB	μ	91.4	88.7	106.3	101.3	99.3	97.8	85.2	80.5	83.9
		σ	4.55	6.51	6.57	4.24	8.18	7.73	7.86	7.04	7.98
	LPB	μ	93.8	93.3	100.4	100.6	102.8	99.1	88.3	83.2	85.3
		σ	4.60	4.66	4.94	2.21	4.35	4.83	5.64	6.99	6.61

2. Artificial Fault Simulations

a. Fault Simulation

In order to assess the 1/1 octave band method, three cases of artificial fault simulation were performed. Before we simulated these cases, we had to define a "fault". For simplicity, we assumed a fault could be approximated with 5 bars, as shown in Figure 15. The bandwidth of the fault is about 4.5 Hz.

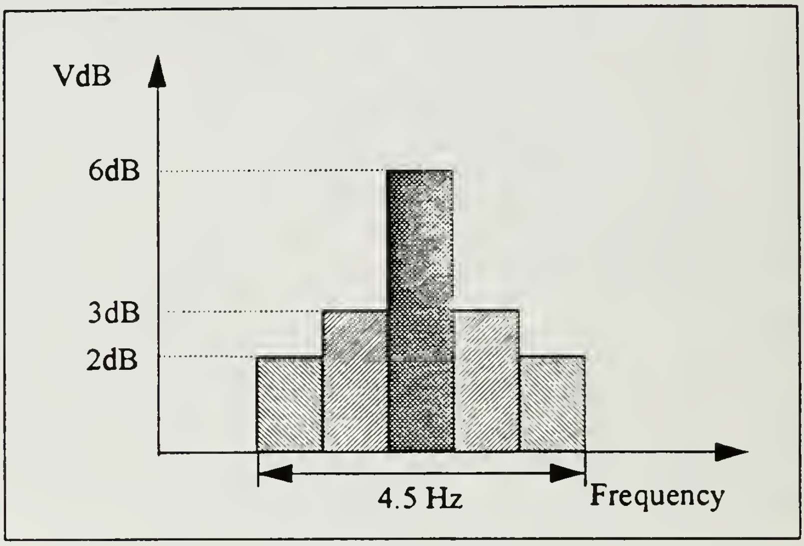


Figure 15 Fault with 6VdB Gain at Center Bar

Based on Eq. (8), if the vibration amplitude doubles with a linear velocity scale then the VdB level will increase 6VdB at the corresponding frequency. Therefore, we defined a fault as having a 6VdB gain at the center bar and use four bars with 3VdB (half the power of the center bar) and 2VdB at the side bands to simulate leakage effects around the corresponding frequency.

b. Simulation of A Misalignment Fault

Misalignment occurs when the center lines of two shafts are offset or meet at an angle. The characteristics of misalignment in a spectrum include:

- High amplitude axial peaks and radial peaks at 1, 2 and 3 orders of shaft RPM.
- Higher harmonics of the shaft RPM (greater than 4 orders of shaft RPM) are generally low in amplitude.

Thus, it is reasonable to add the 6VdB gain fault at the first and second order. Figure 16(a) and 16(b) show the spectrums before and after imposing the fault. Figure 16(c) compares the differences in the 1/1 octave band levels and the 10-5,000 Hz broad band level for these two conditions. As can be seen in Figure 16(c), the 1/1 octave band levels have a 4.46 VdB gain at third band (which corresponds to 1 order of shaft RPM) and a 3.13 VdB gain at the forth band (which corresponds to 2 orders of shaft RPM). However, the 10-5,000 Hz broadband level only increased 2.17 VdB. Obviously, the 1/1 octave band method is more sensitive than broadband method.

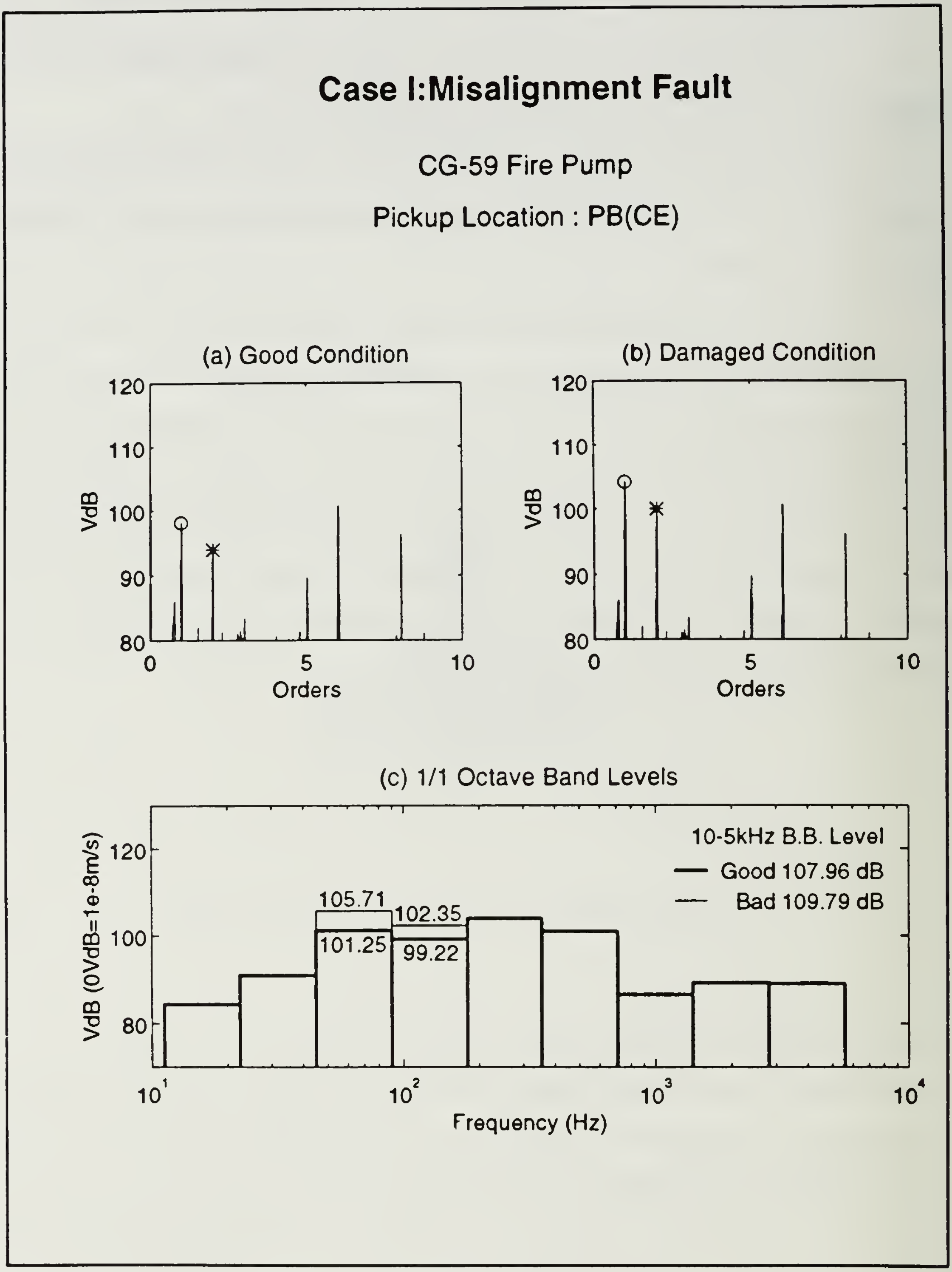


Figure 16 Simulation Result for Artificial Misalignment At Shaft

c. *Simulation of A Looseness Fault At Impeller*

Impeller looseness is a rotating element looseness. The important characteristics of looseness in a spectrum include:

1. Presence of a large number of harmonics.

2. Presence of half-harmonics.

For example, the fire pump of a CG-59 has six impellers contributing to a forcing frequency of 6 orders of the shaft RPM, and we expect higher levels at 6 orders and its harmonics (12 orders, 24 orders,... etc.) for a loose impeller. The levels at half-harmonics (e.g. 3 orders and 9 orders) will also increase. Thus, in this looseness fault simulation, an artificial fault was applied by adding a fault with 6VdB at center bar at the 6th order(i.e. 6 x shaft RPM) and adding two fault with 3VdB at center bar at the 3rd order and the 9th order. Figure 17(a) and 17(b) show the spectrum of good and damaged fire pumps. Figure 17(c) compares the differences in 1/1 octave band levels and the 10-5,000 Hz broadband level for these two conditions. At the fifth of the 1/1 octave band levels, there is a 1.5 VdB gain. However, the 10-5,000 Hz broadband level only increased 0.29 VdB. Again, the 1/1 octave band method is more sensitive than broadband method.

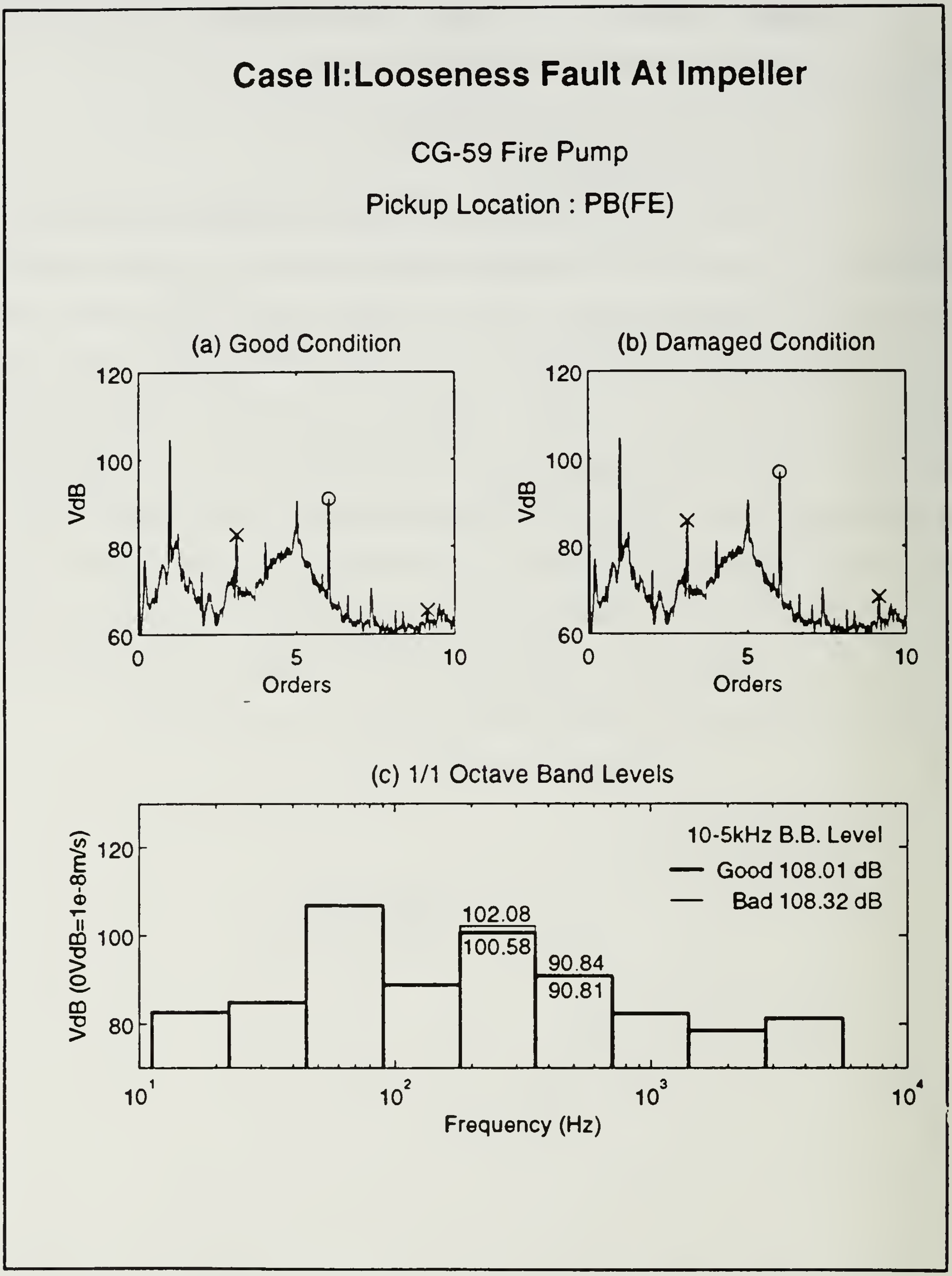


Figure 17 Simulation Result for Artificial Looseness At Impeller

d. Simulation of A Bearing Fault

For a steady state condition, some periodic signatures exist which relate to corresponding bearing faults, called bearing frequencies. These bearing frequencies can be found in the VTAG. In this section, an artificial fault imposed at the motor bearing (free end) of a CG-59 fire pump has been simulated. The bearing frequencies of this bearing are tabulated in Table 17.

TABLE 17: BEARING FREQUENCIES OF MRC310 BEARING

Bearing Frequency	Symbol	Order
Train order of rolling element	f_r	0.38
Relative rotation order of rotating raceway	f_{t1}	0.619
Spin order of rolling elements	f_b	1.98
Irregularity order of rolling element	f_{bs}	3.96
Irregularity order of rotating raceway	f_{ir}	4.95
Irregularity order of stationary raceway	f_{or}	3.04

Suppose, for example, that there is a wear degradation in the inner raceway. Then the presence of the fundamental f_{ir} tone with harmonics would be expected. Figure 18(a) shows the spectrum of a good bearing. The 6VdB fault is imposed at the 4.95 order as shown in Figure 18(b). Figure 18(c) shows the resulting increase in the 1/1 octave band levels. The 4.95 order is located at the fifth of the 1/1 octave bands. The 10-5,000 Hz broadband levels before and after damage are almost unchanged. However, the fifth octave band level has a 1.57VdB increase. This illustrates why a single broadband level cannot be used to determine the condition of a machine.

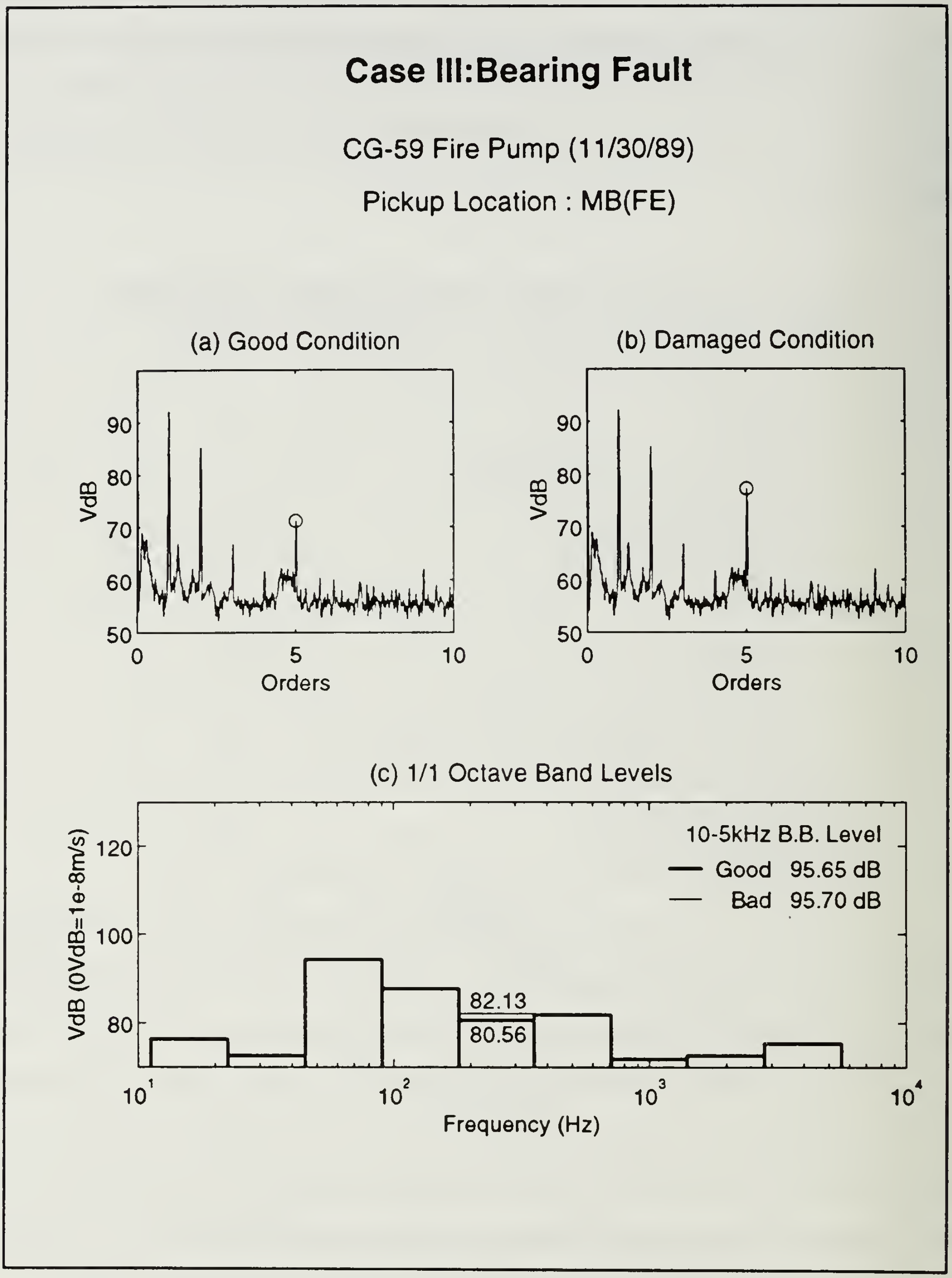


Figure 18 Simulation Result for Artificial Bearing Fault At Motor

V. RESULTS OF USING NAVSSES FREQUENCY DOMAIN DATABASE

Since digital vibration survey instruments are more popular and easy to use than other types, only frequency spectrum reading were recorded and stored into the database. Thus, our 1/1 octave band analysis was performed using frequency domain data. Data measured for the CG-59 fire pumps in six survey dates are available in ASCII format. The total number of fire pumps analyzed was twenty-seven. Table 18 shows the available frequency data and corresponding survey date. Each set of data contains a 10 order and a 100 order spectra. The resolution for each set of data is 400 lines. The averaged spectra using these data are shown in Figure 19 and Figure 20 for each order range. The thin lined curve represents the mean levels and the thick lined curve represents for the mean plus one standard deviation levels. The 10 order spectrum was used to compute the first six 1/1 octave band levels and the 100 orders spectrum was used to compute the seventh and above band levels. Results of the 1/1 octave band analysis for each set of data are shown in Appendix F. A summary of 1/1 octave band analysis results for each pickup location using all the fire pumps is shown in Figure 21. As can be seen from Figure 21, the higher frequency levels (seventh band to ninth band) are about 95 VdB for the motor bearing and 110 VdB for the pump bearing. However, these higher frequency levels in Figure 12 using time waveform tape data are about 80 VdB for the motor bearing and 90 VdB for the pump bearing. As we reviewed the narrow band plot for the NAVSSES frequency domain data, we found that the levels below 54 VdB have been cut off and forced to 54 VdB. This is why levels from using time waveform tape data. Figure 22 shows a good example of a cut off spectrum for a motor bearing using the NAVSSES frequency domain data.

Table 18: DATA COLLECTION SHEET FOR AVAILABLE FREQUENCY DOMAIN DATA FROM NAVSSES DATABASE

Survey Date	Number of Fire Pumps	Number of Pickup Location	Number of Data Set
12-MAY-93	6	5	30
23-FEB-92	5	5	25
21-OCT-90	5	5	25
07-JUN-90	4	5	20
26-FEB-90	1	5	5
30-OCT-89	6	5	30

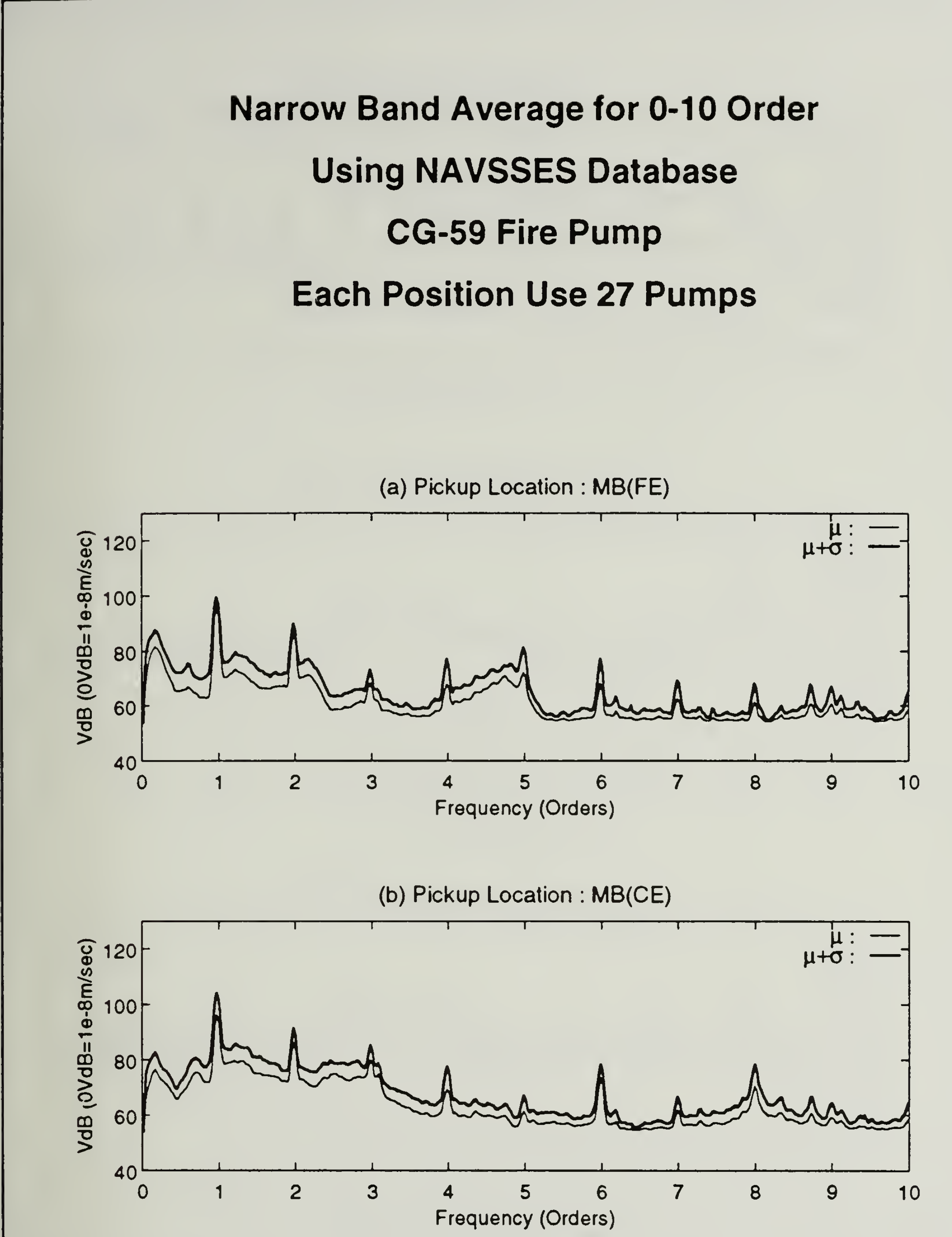


Figure 19 The Averaged Spectra for CG-59 Fire Pumps (0-10 Order) Using Frequency Domain Data

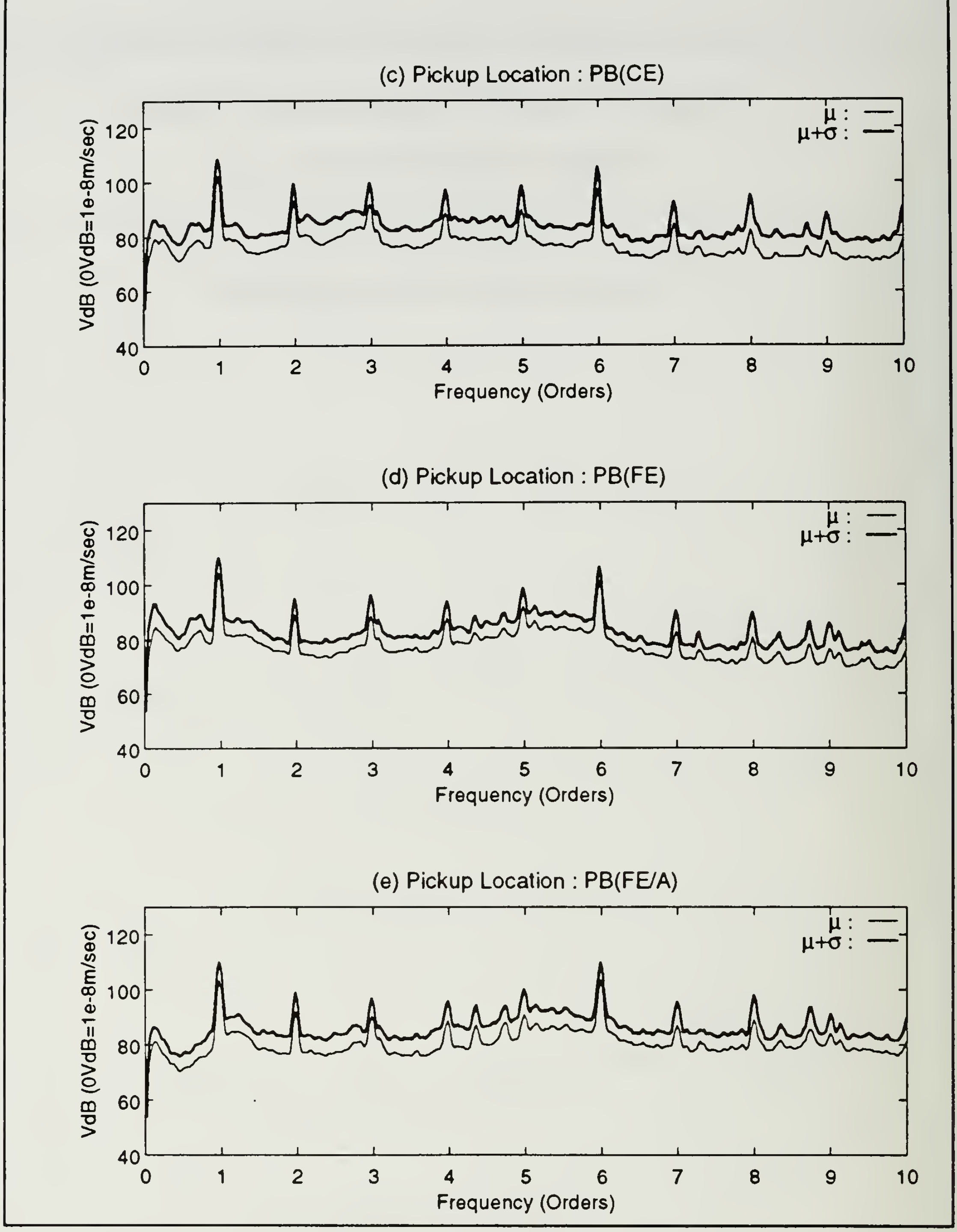


Figure 19 The Averaged Spectra for CG-59 Fire Pumps (0-10 Order) Using Frequency Domain Data (Cont.)

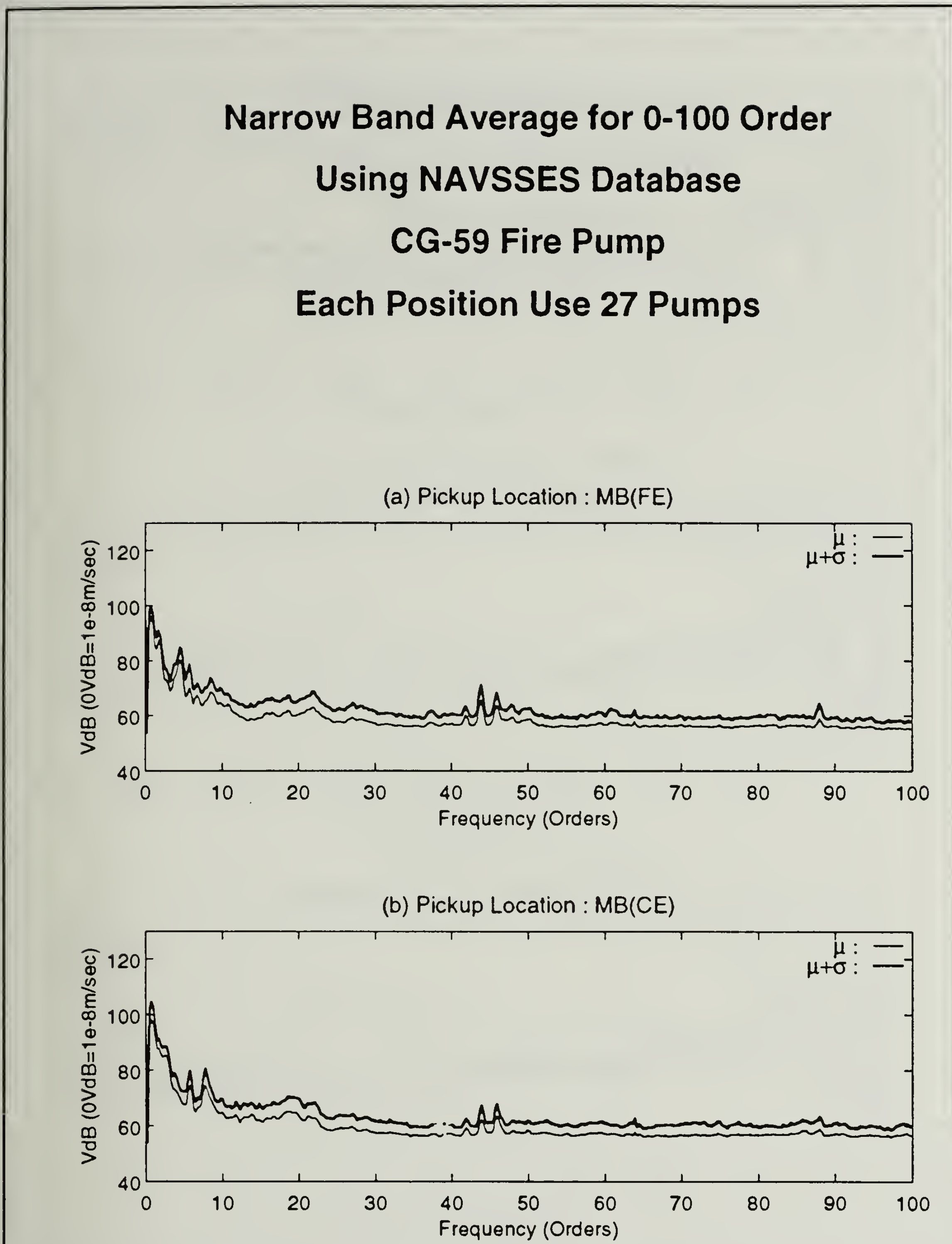


Figure 20 The Averaged Spectra for CG-59 Fire Pumps (0-100 Order) Using Frequency Domain Data

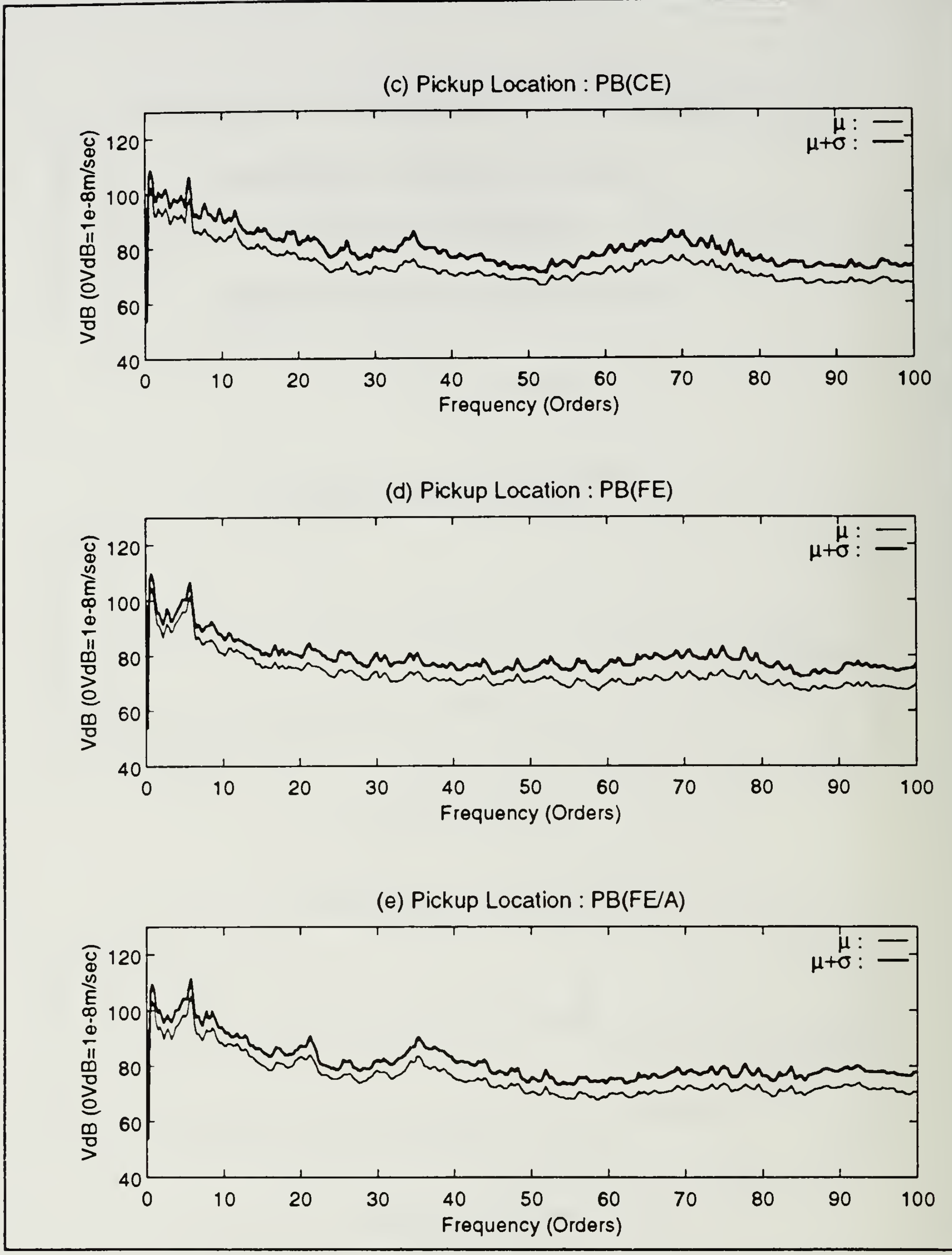


Figure 20 The Averaged Spectra for CG-59 Fire Pumps (0-100 Order) Using Frequency Domain Data (Cont.)

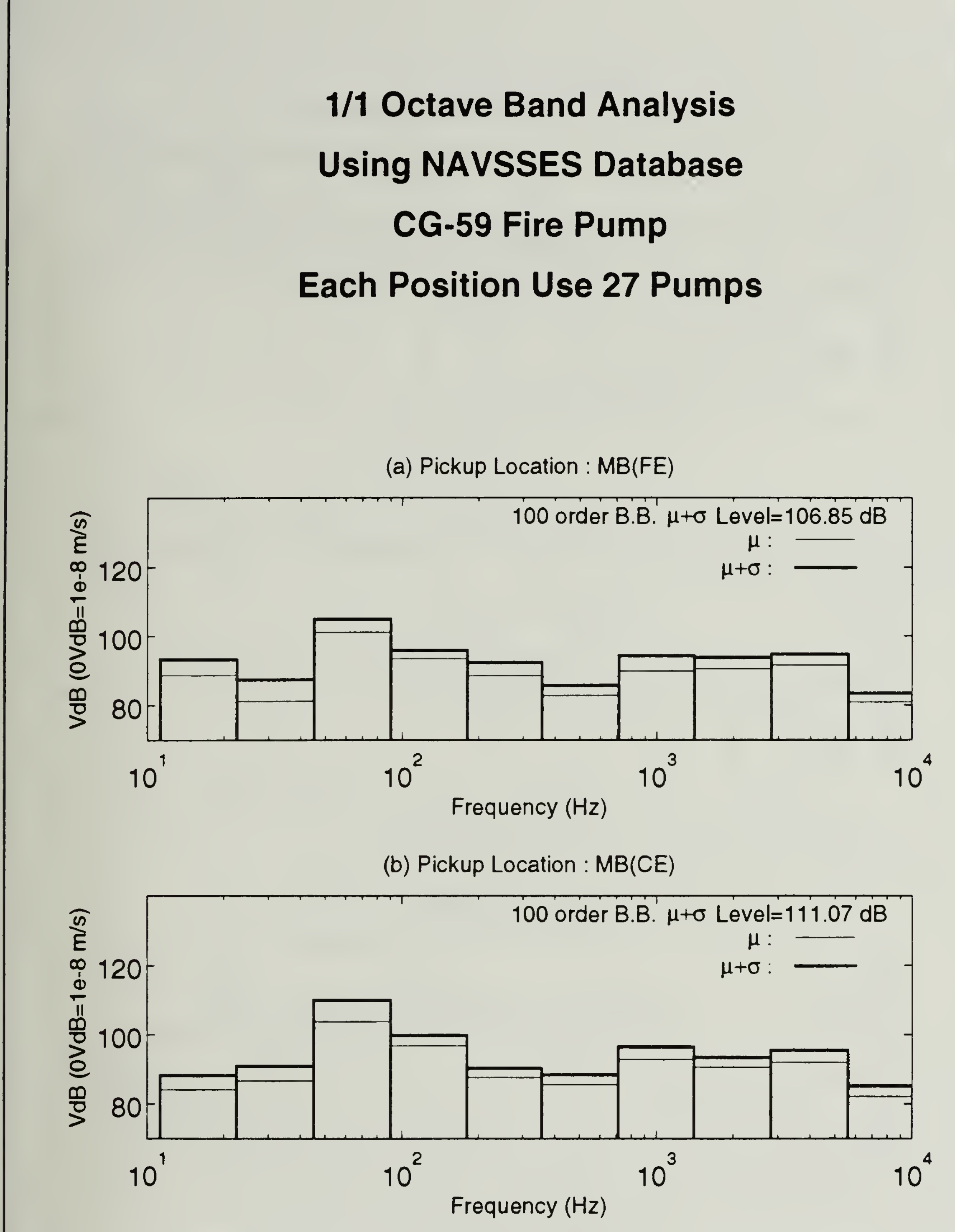


Figure 21 The Summarized 1/1 Octave Band Levels for CG-59 Fire Pumps Using NAVSSES Frequency Domain Data

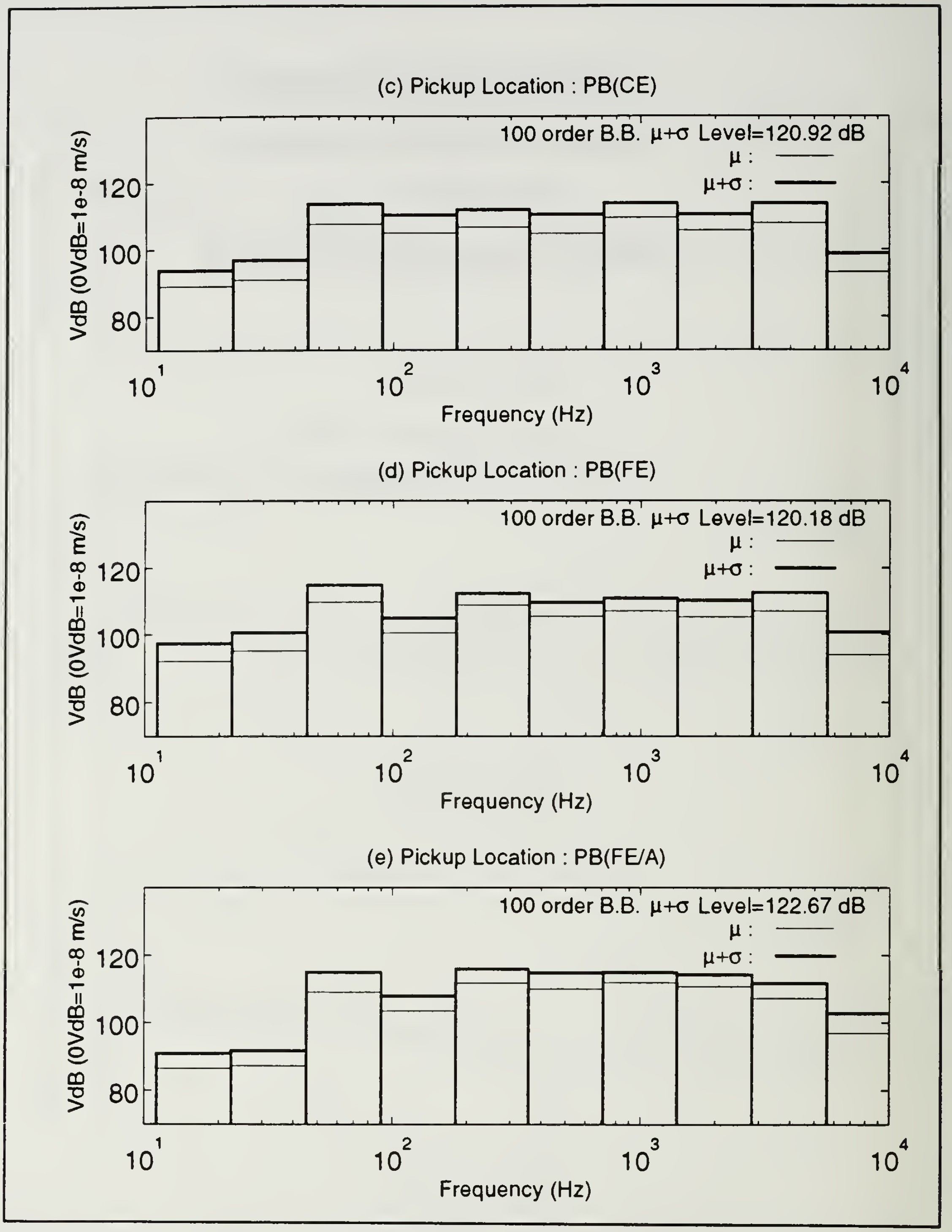


Figure 21 The Summarized 1/1 Octave Band Levels for CG-59 Fire Pumps Using NAVSSES Frequency Domain Data (Cont.)

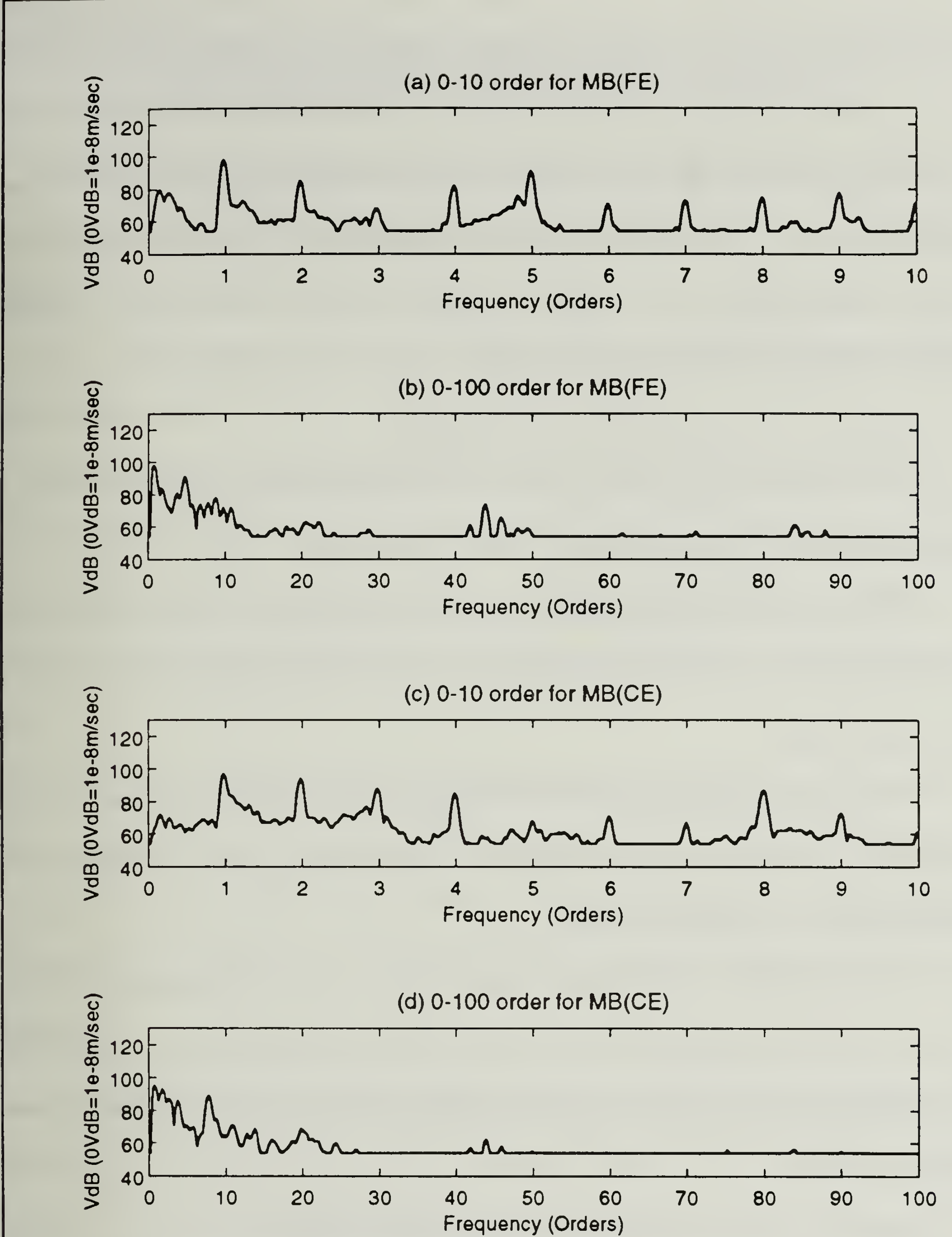


Figure 22 The Narrow Band Spectra for CG-59 Fire Pumps Using NAVSSES Frequency Domain Data Measured at MB(FE) and MB(CE)

VI. CONCLUSIONS AND RECOMMENDATIONS

Both time and frequency domain analyses were performed using fire pump vibration data to determine an appropriate alert level. Cross Peak Analysis in the time domain and 1/1 Octave Band Analysis in the frequency domain were used to set the alert threshold level(s). The following conclusions are drawn:

Time Domain Analysis (Cross Peak Analysis)

a. The measured peak envelop data at five different pickup locations follows a Gaussian probability distribution in the VdB(log) domain well.

b. The $\mu+2\sigma$ value computed using a peak envelop probability density function in the VdB domain gives a broadband peak amplitude alert level rather than the energy content in the vibration signal.

c. We used 12 measured data sets (6 fire pumps and 2 different measurement dates) which were available on cassette data tapes. To improve the quality of averaging, more measured data sets would be required.

d. NAVSSES does not save time domain data on any storage media at this time. However, for some shipboard machinery, such as low and high pressure air compressors, time domain data is required to cast measured data in the time-frequency domain to detect the possible faults.

Frequency Domain Analysis (1/1 Octave Band Analysis)

a. 1/1 Octave Band Analysis (OBA) uses nine frequency band alert levels which provides more detailed information about machine condition than the simple broadband frequency band or bands, narrow band zoom mode analysis can be performed for the selected frequency band(s) to identify the component(s) which may have faults.

b. OBA divides the frequency range into 10 bins over 10kHz. The VdB level in each frequency bin is quite sensitive to changes in the energy content of the measured vibration signal.

c. The OBA approach can be easily incorporated into the Digital Vibration Survey Instrument (DVSI).

d. Five sets (27 fire pumps) of 400 line frequency domain DVSI data were received from NAVSSES and OBA was performed. The VdB levels in the higher frequency bins were generally high. This was caused by the fact that the vibration signals which were lower than the VdB limit(54 VdB) were set to the lower VdB limit in a specified dynamic range.

e. OBA was also performed using time domain data obtained from cassette data tapes. The changes in VdB levels at a particular frequency and the corresponding sidebands were introduced in narrow band FFT. The results are transferred into the octave band domain and the sensitivity in VdB levels in frequency bins was analyzed. The results are quite promising.

f. NAVSSES maintains 400 line frequency domain data for all machineries in a graphics postscript format, not in ASCII or digitized format. It was not possible to convert this graphics format data to ASCII format.

Based on current studies, the following recommendations are made:

saved using DVSI. However, for some shipboard machinery such as low and high pressure air compressors, time domain data is required to cast the measured data into the time-frequency domain to detect the possible faults. We suggest saving time domain data for the limited number of shipboard machinery.

b. We suggest implementing the 1/1 Octave Band Analysis Method in DVSI.

c. NAVSSES maintains 400 line frequency domain data for all machinery in graphics postscript format, not in ASCII or digitized format. It was not possible to convert this graphics format data to ASCII format. We suggest saving future files in ASCII format to permit further analysis of the data.

d. We suggest saving/storing DVSI data "as is", without alteration.

APPENDIX A. MATLAB PROGRAM CODE

A. ON-LINE HELP DOCUMENTATION

This section of the guide contains all of the MATLAB functions that we have developed during this research. Each function contains a purpose, synopsis and description in alphabetical order. The MATLAB built-in functions used in these programs are described in the MATLAB reference guide.

The code was written for the MATLAB 4.0 version. For those who want to use these programs in older versions need to consult the MATLAB reference guide for necessary modifications.

Purpose

kurtosis or fourth moment of vectors and matrices.

Synopsis

kurtosis=kurt(x)

Description

krut calculates the kurtosis or fouth moment value.

For vectors, kurt(x) is the kurtosis value of the elements in vector x. For matrices, kurt(x) is a row vector containing the kurtosis value of each column.

Purpose

Plot 1/1 octave band bar plot

Synopsis

logbar(Vdb)

logbar(Vdb,LineStyle)

logbar(Vdb,LineStyle,LineWidth)

Description

logbar(Vdb) draws a 1/1 octave band bar plot using Vdb as the y axis and the ANSI preferred center frequencies and pass bands as the x axis. LineStyle and LineWidth are optinal parameters. The default LineStyle is a solid line. See "plot" for more information about LineStyle. The default LineWidth is 0.5.

3. mstat

Purpose

Statistical analysis for time domain data.

Synopsis

mstat(y,fs,nbar,id)

mstat(y,fs,nbar,id,manaly,mid,locat,mregen,pri)

Description

mstat(y,fs,nbar,mid,locat,manaly,mthre,z,mregen,pri) will analyze the original data *y* using the *manaly* method and produce a statistical report with a *nbar* pdf plot.

mstat(y) allows the user to execute the program in an interactive way.

y	amplitude (calibrated velocity data)
fs	sampling frequency (Hz)
nbar	number of bars in Probability. Density Distribution Plot
mid	type of machinery
locat	pickup location
manaly	method of analysis
	=1 means All data points analysis
	=2 means Overall peak points analysis
	=3 means Cross peak points analysis
mthre	with threshold or not
	=1 without threshold
	=2 with threshold
z	percentage of threshold
mregen	transform to Vdb or not
	=1 without transform
	=2 transform to Vdb domain
pri	print or not (‘y’es or ‘n’o)

Purpose

Cross peak points.

Synopsis

ypc=npc(y)

Description

ycp=npc(y) will find the peak points between each two zero-crossing..

y	original data
ycp	cross peak data

Purpose

Overall peak points

Synopsis

yp=npeak(y)

Description

yp=mpeak(y) will find the overall peak points.

y	original data
yp	overall peak data

Purpose

Threshold

Synopsis

yt=nthre(y,z)

Description

yt=nthre(y,z) will remove the points with z% threshold .

y	original data
yt	data after threshold
z	percentage of the threshold If z=1 then the program will remove the peak data small than 1% of the maxinum peak value.

Purpose

1/1 octave band level.

Synopsis

oct=octave(y)

oct=octave(y,i_1,i_2)

Description

oct=OCTAVE(y) returns the 1/1 octave band Vdb values from band 1 to band 10.

oct=OCTAVE(y,i_1,i_2) returns the 1/1 octave band Vdb values from band i_1 to band i_2 and the others bands will be assigned a value of 0.

y(:,1) : Vdb values

y(:,2) : frequencies

Purpose

To evaluate the averaging VdB values using hanning window.

Synopsis

VdB=psd(y,nblock)

Description

VdB=psd(*y*,*nblock*) returns the average VdB values using time domain data *y*. The number of averagings is specified by *nblock*. The recommend number of averagings is 20. The data matrix *y* must be a 2^n by 2 matrix. *y(:,1)* contains time series and *y(:,2)* contains corresponding velocity data. The hanning window is used to damp out the effects of the Gibbs phenomenon. The reference 0VdB is 10^{-8} m/sec.

Purpose

Skewness or third moment.

Synopsis

skewness=skew(x)

Description

skew calculates the skewness or third moment value.

For vectors, skew(x) is the skewness value of the elements in vector x.

For matrices, skew(x) is a row vector containing the skewness value of each column.

Purpose

Plot time series and frequency spectrum.

Synopsis

[Ya,y,fx]=transfer(yo,t,fo,nblock,sec)

Description

transfer(yo,t,fo,nblock,sec) return three vectors, plot time series and frequency spectrum. The return vectors are:

Ya	averaged fft vector of yo
y	calibrated velocity vector
fx	frequency vector

The input parameters include:

yo	original amplitude
t	time series corresponds to yo
fo	operating frequency (Hz)
nblock	number of data blocks
sec	interested frequency sections

The spectrum will indicate the peak position assign in sec. For example, input sec=[5 150], the program will search the peak point between 5 Hz and 150 Hz.

1. kurt.m

```
function kurtosis = kurt(y)
% KURT Kurtosis.
% For vectors, KURT(y) returns the kurtosis.
% For matrices, KURT(y) is a row vector containing
% the kurtosis of each column. See also COV.

% Chao-Shih Liu 4-26-93

[n,m]=size(y);
if n==1
   y=y';
   [n,m]=size(y);
end
for i=1:m
   meany(:,i)=mean(y(:,i)).*ones(n,1);
   stdy(:,i)=std(y(:,i))*ones(n,1);
end
s=((y-meany)./stdy).^4;
kurtosis = sum(s)/n;
end
```

```
function logbar(Vdb,LineStyle,LineWidth)
%
% logbar Plot 1/1 octave band bar plot using semilog in
%                    x axis(freq.) and linear scale in Y axis(Vdb)
%
% logbar(Vdb) plots the semilog bar plot
%                    for 1/1 octave band analysis.
%
% logbar(Vdb,LineStyle) plots the semilog bar plot
% for 1/1 octave band analysis with various
% types. See "plot" for more about LineStyle
%
% LineWidth is a optional parameter to control the line
% width of the bar. Default value is 0.5
%

% Written By Liu,Chao-Shih 7/27/93

if nargin<2
  lineStyle='-';
end
if nargin==1
  linewidth=0.5;
end

%
% Define the upper and lower limit of the pass bands (Hz)
%
flow=[11.2 22.4 45 90 180 355 710 1400 2800 5600],
fhigh=[flow(2:10) 10000];

%
% Determine the coordinates of the bars
%
xl=flow(:);
xh=fhigh(:);
y=Vdb(:);
[n,m]=size(y);
n3=n*3,
yy=zeros(n3+1,m);
xx=yy;
xx(1:3:n3,:)=xl(1:n);
xx(2:3:n3,:)=xh(1:n);
xx(3:3:n3,:)=xh(1:n);
xx=[xl(1);xx];
yy(1:3:n3,:)=y;
yy(2:3:n3,:)=y;
yy=[0;yy];
set(semilogx(xx,yy,LineStyle),'linewidth',LineWidth)
end
```

```
function mstat(y,fs,nbar,mid,locat,manaly,mthre,z,mregen,pri)
%
% mstat(y,fs,nbar,mid,locat,manaly,mthre,z,mregen,pri)
% will analysis the original data y and produce a
% statistical report with a nbar pdf plot.
%
% mstat(y) will allow the user to perform the program in an
% interactive way.
%
% y : amplitude (after calibration)
% fs : sampling frequency (Hz)
% nbar : number of bars in Prob. Density Distribution Plot
% mid : type of machinery
% locat : pickup location
% manaly: method of analysis
% =1 means All data points analysis
% =2 means Overall peak points analysis
% =3 means Cross peak points analysis
% mthre : with threshold or not
% =1 without threshold
% =2 with threshold
% z : percentage of threshold
% mregen: transform to Vdb or not
% =1 without transform
% =2 transform to Vdb domain
% pri : print or not
% ='y' means to print out the result

%
% Liu,Chao-Shih 6/7/93
%

if nargin==1
 fs=input('Input the sampling frequency ? (Hz)');
 nbar=input('Input the number of bar used in the PDF plot ?');
 mid=input('Input the type of the machinery ?','s');
 locat=input('Input the pickup location ?','s');
 manaly=menu('Choose the method of analysis',...
 'All data points analysis',...
 'Overall peak analysis',...
 'Cross peak analysis');
 mthre=menu('Type of the threshold ?',...
 'Without threshold',...
 'With n% threshold');
 if mthre==2
 z=input('Input the % of the threshold');z=z/100;
 end
 mregen=menu('Transform the data ?',...
 'Original data',...
 'Vdb Domain');
end

%
```

```
if manaly==1
 yp=y;
 mt='All data points'
 elseif manaly==2
 yp=npeak(y);
 mt='Overall peak';
 else
 yp=npc(y);
 mt='Cross peak';
end

%
% Type of threshold
%
if mthre==1
 tht=' without threshold';
else
 tht=[' with ' num2str(z*100) '% threshold'];
 yp=nthre(yp,z);
end
pnumber=length(yp);

%
% Compute the first four mements for linear domain
%
yp=abs(yp);
mepx=['m=' num2str(mean(yp))];
stdpx=['s=' num2str(std(yp))];
skewpx=['Skewness=' num2str(skew(yp))];
kurtpx=['Kurtosis=' num2str(kurt(yp))];

%
% Compute the first four moments for Vdb Domain
%
if mregen==2
 yr=20*log10(yp/1e-8);
 meanyr=mean(yr);stdyr=std(yr);
 skewyr=skew(yr);kurtyr=kurt(yr);
 merpx=['m = ' num2str(mean(yr))];
 stdrpx=['s = ' num2str(std(yr))];
 skewrpx=['Skewness=' num2str(skew(yr))];
 kurtrpx=['Kurtosis=' num2str(kurt(yr))];
end

%
% Plot the overall envelope PDF
%
clg,
if mregen==1
 subplot(312)
 [av,au]=hist(yp,nbar);bar(au,av);
 ylabel('Probability');xlabel('Velocity (m/sec)');
 title('Original Data(x) Envelope');
```

```
 set(text(0.3,1,mepx),'fontn','symbol','fonta','italic');
 set(text(0.3,0.8,stdpx),'fontn','symbol','fonta','italic');
 set(text(0.3,0.6,skewpx),'fontn','times','fonta','italic');
 set(text(0.3,0.4,kurtpx),'fontn','times','fonta','italic');
else
 subplot(323)
 [av,au]=hist(yp,nbar);bar(au,av);
 ylabel('Probability');xlabel('Velocity (m/sec)');
 title('(a) Linear Domain');
 subplot(324)
 [av,au]=hist(yr,nbar);bar(au,av);
 ylabel('Probability');xlabel('Vdb (0Vdb=1e-8 m/sec)');
 title('(b) Vdb Domain');
 subplot(313);axis('off');
 set(text(0.1,1,mepx),'fontn','symbol','fonta','italic');
 set(text(0.1,0.8,stdpx),'fontn','symbol','fonta','italic');
 set(text(0.1,0.6,skewpx),'fontn','times','fonta','italic');
 set(text(0.1,0.4,kurtpx),'fontn','times','fonta','italic');
 set(text(0.7,1,merpx),'fontn','symbol','fonta','italic');
 set(text(0.7,0.8,stdrpx),'fontn','symbol','fonta','italic');
 set(text(0.7,0.6,skewrpx),'fontn','times','fonta','italic');
 set(text(0.7,0.4,kurtrpx),'fontn','times','fonta','italic');
end

%
% Statistical analysis results
%
subplot(311),axis('off');
ta1=['Statistical Analysis Results for ' mid];
set(text(0.5,1,ta1),'fontsi',14,'fontw','bold','hori','c');
loc=['Pickup Location : ' locat],
set(text(0.5,0.8,loc),'fontsi',14,'fontw','bold','hori','c');
ta2=['Data analysis by using : ' mt tht];
set(text(0.5,0.4,ta2),'hori','c');
block=['Number of data points : ' num2str(pnumber)];
set(text(0.5,0.2,block),'hori','c');
frange=['The sampling frequency : ' num2str(fs) ' Hz'];
set(text(0.5,0,frange),'hori','c');

%
% Print the graph or not
%
if nargin<4
 pri=input('Print the plot ? (y/n)','s');
end
if pri=='y'
 set(1,'PaperPosition',[1.25 2 6 8.5])
 print -f1
end
end
```

```
function ycp=npc(y)
%
% ycp=npc(y) will find the peak points between each two
% zero-crossing.
%
% y : original data
% ycp : cross peak data
%

%
% Liu,Chao-Shih 4/26/93
%

y=y(:);
k=length(y);
y=y-mean(y)*ones(k,1);
npc=0;l=1;
ycp=zeros(k,1);
for n=2:k
 if sign(y(n)*y(n-1))==-1
 h=n-1;npc=npc+1;
 [yp,np]=max(abs(y(l:h)));
 np=np+l-1;
 ycp(npc)=y(np);
 l=h+1;
 end
end
ycp=ycp(1:npc);
end
```

```
function yp=mpeak(y)
%
% yp=mpeak(y) will find the overall peak points.
%
% y : original data
% yp : overall peak data
%

%
% Liu,Chao-Shih 4/14/93
%

y=y(:);
k=length(y);
y=y-mean(y)*ones(length(k),1);
yp=zeros(k,1);
yp(1)=y(1);
pc=1;
for n=2:k-1
 ns1=n-1;
 n1=sign((y(n+1)-y(n))*(y(n)-y(ns1)));
 if n1==-1 | y(n)==y(ns1)
 pc=pc+1;yp(pc)=y(n);
 end
end
yp=yp(1:pc,1);
end
```

3. nthre.m

```
function yt=nthre(y,z)
%
% yt=nthre(y,z) will remove the points with z% threshold
%
% y : original data
% yt : data after threshold
% z : percentage of the threshold
% If z=1 then the program will not return the peak
% peak data small than 1% of the maxinum peak value.

%
% Liu,Chao-Shih 4/14/93
%
y=sort(y(:));
ly=length(y);
maxy=max(y);
miny=z*0.01*maxy;
for l=1:ly
 if y(l)>=miny
 po=l;
 yt=y(po:ly,1);
 break
 end
end
```

```
function oct=octave(y,i1,i2)
%
% OCTAVE Octave band.
%
% oct=OCTAVE(y) returns the 1/1 octave band Vdb values from
% band 1 to band 10.
%
% oct=OCTAVE(y,i1,i2) returns the 1/1 octave band Vdb values
% from band i1 to band i2 and the others
% bands will be assigned to 0.
%
% y(:,1) : Vdb values
% y(:,2) : frequencies

%
% Chao-Shih Liu 7/13/93
%

fc=[16 31.5 63 125 250 500 1000 2000 4000 8000];
flow=[11.2 22.4 45 90 180 355 710 1400 2800 5600];
fhigh=[22.4 45 90 180 355 710 1400 2800 5600 11200];
np=max(size(y));
oct=zeros(10,1);

%
% Default the i1 and i2
%
if nargin==1
 i1=1;i2=10;
end

%
% if Vdb lower than 0 db, force the value=0db
%
for k=1:np
 if y(k,1)<0
 y(k,1)=0;
 end
end

%
% convert to linear velocity value
%
vref=1e-8;
y(:,1)=10.^(y(:,1)/20)*vref;
fmax=y(np,2);df=fmax/(np-1);

%
% calculate the 1/1 octave band levels
%
df2=df/2;
fupper=y(:,2)+df2; % Upper limit of frequency
flower=y(:,2)-df2; % Lower limit of frequency
```

```
for k=i1:i2;
 mark1=fupper-flow(k);
 mark2=flower-flow(k);
 mark3=fupper-fhigh(k);
 mark4=flower-fhigh(k);
 for j=1:np
 if mark4(j)>=0 % larger than the band(k)
 break
 else
 if mark1(j)<=0 % smaller than the band(k)
 % do nothing
 else % cover the band(k)
 if mark3(j)>0
 if mark2(j)<0 % band(k) smaller than df
 sum(k)=y(j,1)^2*(fhigh(k)-flow(k));
 break;
 else % partial band in band(k+1)
 sum(k)=sum(k)+y(j,1)^2*abs(mark4(j));
 end
 else
 if mark2(j)<0 % partial band in band(k-1)
 sum(k)=y(j,1)^2*mark1(j);
 else
 sum(k)=sum(k)+y(j,1)^2*df;
 end
 end
 end
 end
 end
oct(k)=20*log10(sqrt(sum(k))/vref);
end

bar(oct)
xlabel('Number of Center Frequency')
ylabel('Vdb value (0Vdb=1e-8 m/sec)')
axis([i1-1 i2+1 40 120])
for k=i1:i2
 octext=sprintf('%5.1f',oct(k));
 set(text(k,oct(k)+2,octext),'fontw','bold','horiz','center')
end
```

```
function Vdb=psd(y,nblock)
% Vdb=PSD(y,nblock)
%
% This function will compute the average Vdb value by
% using hanning to nblock data set.
%
% y : original data matrix (time,velocity)
% nblock : number of data blocks
% Ya : average fft Vdb vector of y(0Vdb=1e-8 m/sec)
% fx : frequency vector
%
% Liu,Chao-Shih 12:11PM 7/14/93
%

% standardize the data matrix
n=size(y,2);
if n~=2
 y=y';
end

t=y(:,1);y=y(:,2);
dt=t(2)-t(1);
fs=1/dt;
vref=1e-8;

%
% Compute the fft data
%
n=length(y)/nblock;n2=n/2;
nl=1;
w=hanning(n);
for nb=1:nblock
 nh=nb*n;
 Y(1:n,nb)=fft(w.*y(nl:nh,1))*dt;
 nl=nh+1;
end
if nblock~=1
 Y=(sum(abs(Y)')/nblock)';
else
 Y=abs(Y);
end
Ya=20*log10(2*Y/vref);
f=fs/2*(0:n2)/n2;
Ya(n2+2:n)=[];
fx=f(2:n2+1)';
df=fx(2)-fx(1);
fx=[0;fx];
Vdb=[Ya,fx];
```

```
function skewness = skew(y)
%SKEW Skewness. For vectors, SKEW(y) returns the skewness.
% For matrices, STD(y) is a row vector containing
% the skewness of each column. See also COV.

% Chao-Shih Liu 4-26-93

[n,m]=size(y);
if n==1
 y=y';
 [n,m]=size(y);
end
for i=1:m
 meany(:,i)=mean(y(:,i)).*ones(n,1);
 stdy(:,i)=std(y(:,i))*ones(n,1);
end
s=((y-meany)./stdy).^3;
skewness = sum(s)/n;
end
```

```
function [Ya,y,fx]=transfer(yo,t,fo,nblock,sec)
% [Ya,y,fx]=transfer(yo,t,fo,nblock,sec)
%
% This function will plot time & frequency domain
%
% yo : original velocity vector (before calibration)
% t : time vector
% fs : sample frequency
% fo : operation frequency = RPM/60
% nblock : number of data blocks
% Ya : average fft vector of y
% fx : frequency vector
% y : original velocity vector (after calibration)
%
% Liu,Chao-Shih 1:58 7/10/93
%

dt=t(2)-t(1);
fs=1/dt;
itext=input('Input the title of this record =>','s');
locat=input('Input the location of data collect','s');
y=yo;
scale=menu('Choose the method of X scale','Frequency (Hz)','Order');
vref=1e-8;

%
% Standarized the size of y
%
[xd,yd]=size(y);
if yd~=1
 y=y';t=t';
end
ny=length(y);

%
% Compute the fft data
%
n=ny/nblock;n2=n/2;
nl=1;
win=menu('Type of Window System','Without window system',...
 'Hanning window','Hamming window');
if win==1
 w=ones(n,1);
elseif win==2
 w=hanning(n);
else
 w=hamming(n);
end
for nb=1:nblock
 nh=nb*n;
 Y(1:n,nb)=fft(w.*y(nl:nh,1))*dt,
 nl=nh+1;
end
```

```
Y=sum(abs(Y'))/nblock;
else
 Y=abs(Y);
end
Ya=20*log10(2*Y/vref);
f=fs/2*(0:n2)/n2;
Ya(n2+2:n)=[];
if scale==1
 fx=f(2:n2+1);
 df=fx(2)-fx(1);
 xt='Frequency (Hz)';unit=' Hz ';
 else
 fx=f(2:n2+1)/fo;
 df=fx(2)-fx(1);
 low=ceil(0.75/df);high=ceil(1.25/df);
 [Ymax,Ypos]=max(Ya(low:high));fscale=fx(low+Ypos-1);
 fx=fx/fscale;fo=fo*fscale;
 xt=['Frequency (Normalized Orders)'];unit=' Order ';
end
df=fx(2)-fx(1);
sec=ceil(sec/df);
if sec(1)==0
 sec(1)=1;
end
for mk=1:length(sec)-1
 [mav(mk),pos(mk)]=max(Ya(sec(mk):sec(mk+1)));
 pos(mk)=pos(mk)+sec(mk);
end

%
% Plot time domain and frequency domain
%
figure(1);clf;subplot(212);
tf=1024;
if ny<1024
 tf=ny;
end
plot(t(1:tf,1),y(1:tf,1),'r');axis([t(1,1) t(tf,1) min(y) max(y)]);
title('Time Domain');xlabel('Time (sec)');ylabel('Velocity(m/sec)');grid
%
% General information
%
subplot(211);axis('off')
mfo=['The operation condition = ' num2str(fo*60)...
 ' RPM (= ' num2str(fo) ' Hz)'];
mloc=['Data pickup location = ' locat];
mfs=['Data sampling frequency = ' num2str(fs) ' Hz'];
mdp=['Total number of sampling data points = ' num2str(length(y))];
set(text(0.5,1,itext),'fontsi',15,'fontw','bold','horiz','center')
text(0.05,0.9,mloc);text(0.05,0.82,mfo);
text(0.05,0.74,mfs);text(0.05,0.66,mdp);

text(0,0.5,'* The time domain');
mt=['Mean value = ' num2str(mean(y)) ' m/sec'];
```

```
text(0.05,0.4,mt);
st=['Standard deviation = ' num2str(std(y)) ' m/sec'];
text(0.05,0.32,st);
text(0.05,0.24,['The plot only shown ' num2str(tf) ' data points']);
pause

figure(2);clf;subplot(212);
plot(fx,Ya(2:n2+1),'r');
upper=(ceil((max(mav))/10)+1)*10;
axis([0 fx(n2) 20 upper]);
title('Frequency Domain');xlabel(xt);ylabel('Velocity in Vdb');grid
for lop=1:length(sec)-1
 text(fx(pos(lop)-1),mav(lop),num2str(lop));
end

%
% General information
%
subplot(211);axis('off')
mfo=['The operation condition = ' num2str(fo*60)...
 ' RPM (= ' num2str(fo) ' Hz)'];
mloc=['Data pickup location = ' locat];
mfs=['Data sampling frequency = ' num2str(fs) ' Hz'];
mbk=['Number of data block averages = ' num2str(nblock)];
mdp=['Block size = ' num2str(length(y)/nblock) ' points/block'];
set(text(0.5,1,itext),'fontsi',15,'fontw','bold','horiz','center');
text(0.05,0.9,mloc);text(0.05,0.82,mfo);
text(0.05,0.74,mfs);text(0.05,0.66,mbk);text(0.05,0.58,mdp);
text(0,0.5,'* The frequency domain');
for lop=1:length(sec)-1
 as=[num2str(lop),' = (',num2str(fx(pos(lop)-1)),...
 unit,', ',num2str(mav(lop)),' db)'];
 if lop>4
 xpos=0.55;ypos=0.8-0.08*lop;
 else
 xpos=0.05;ypos=0.48-0.08*lop;
 end
 text(xpos,ypos,as);
end
morder=['1 order = ' num2str(fo) ' Hz'];
text(0.05,0.08,morder);
mref=['The reference 0 Vdb = ' num2str(vref) ' m/sec'];
text(0.05,0,mref);
%
% zooming up the plot ?
%
zoom=1;
while zoom~=3
subplot(212)
zoom=menu('zoom up ?','0-10 order',...
 'Use mouse to select the range','No');
 if zoom==1
 axis([0 10 20 upper]);
 elseif zoom==2
 axis([0 fx(n2) 20 upper]);
```

```
xrange=sort(xs);
 if xrange(1)<0
 xrange(1)=0;
 end
 axis([xrange(1) xrange(2) 20 upper]);
 else
 break
 end
end
%
% Print out the plot
%
uiprint=[ 'set(1,''PaperPosition'',[0.25 1 8 9.25]);' 'print -f1;' ...
 'set(2,''PaperPosition'',[0.25 1 8 9.25]);' 'print -f2;' 'end'];
uicontrol('style','push','units','normal','pos',[0.9 0.9 0.08 0.06], ...
 'string','print','call',uiprint);
uicontrol('style','push','units','normal','pos',[0.9 0.82 0.08 0.06], ...
 'string','exit','call','end');
```

APPENDIX B. EXAMPLES OF USING MATLAB PROGRAM IN PC486

MATLAB allows the user to write a *script* file. A *script* file is an external file that contains a sequence of MATLAB statements. The following example will show the *script* files used to perform the analysis.

A. CROSS PEAK ANALYSIS EXAMPLE

In this example, a CG-59 fire pump measured at MB(FE) data set is used in the analysis. The file name of the data file is *f1p1.asc*. The MATLAB command is anchored by >>.

```
>> load f1p1.asc
>> y=f1p1(:,2);
>> t=f1p1(:,1);
>> mstat(y)
```

The user can then interact with the program to select the method of analysis. Instead of this interactive process, the user can use the following to execute the program in an automatic way.

```
>> load f1p1.asc
>> y=f1p1(:,2);
>> t=f1p1(:,1);
>> ypc=npc(y);
>> yt=nthre(ypc,1);
>> mid='CG-59 Fire Pump';
>> locat='MB(FE)';
```

B. 1/1 OCTAVE BAND ANALYSIS EXAMPLE

Here, proceeding as in the above example, a CG-59 fire pump measured at MB(FE) data set is used to perform the 1/1 octave band analysis. The file name of the data file is *f1p1.asc*. The MATLAB command is anchored by >>.

```
>> load f1p1.asc
>> yh=f1p1(:,2);                     % yh is a time series sampled at 10 kHz.
>> yl=yh(1:5:length(yh));            % yl  is a time series sampled at 2 kHz.
>> t=f1p1(:,1);
>> VdBh=psd(yh,20);
>> VdBl=psd(yl,20);
>> octh=octave(VdBh,7,9);
>> octl=octave(Vdbl,1,6);
>> octband=[octh octl];
>> logbar(octband);
```

APPENDIX C. FIGURES OF PROBABILITY DISTRIBUTION OF CROSS PEAK POINTS

This section contains all the cross peak distribution figures.

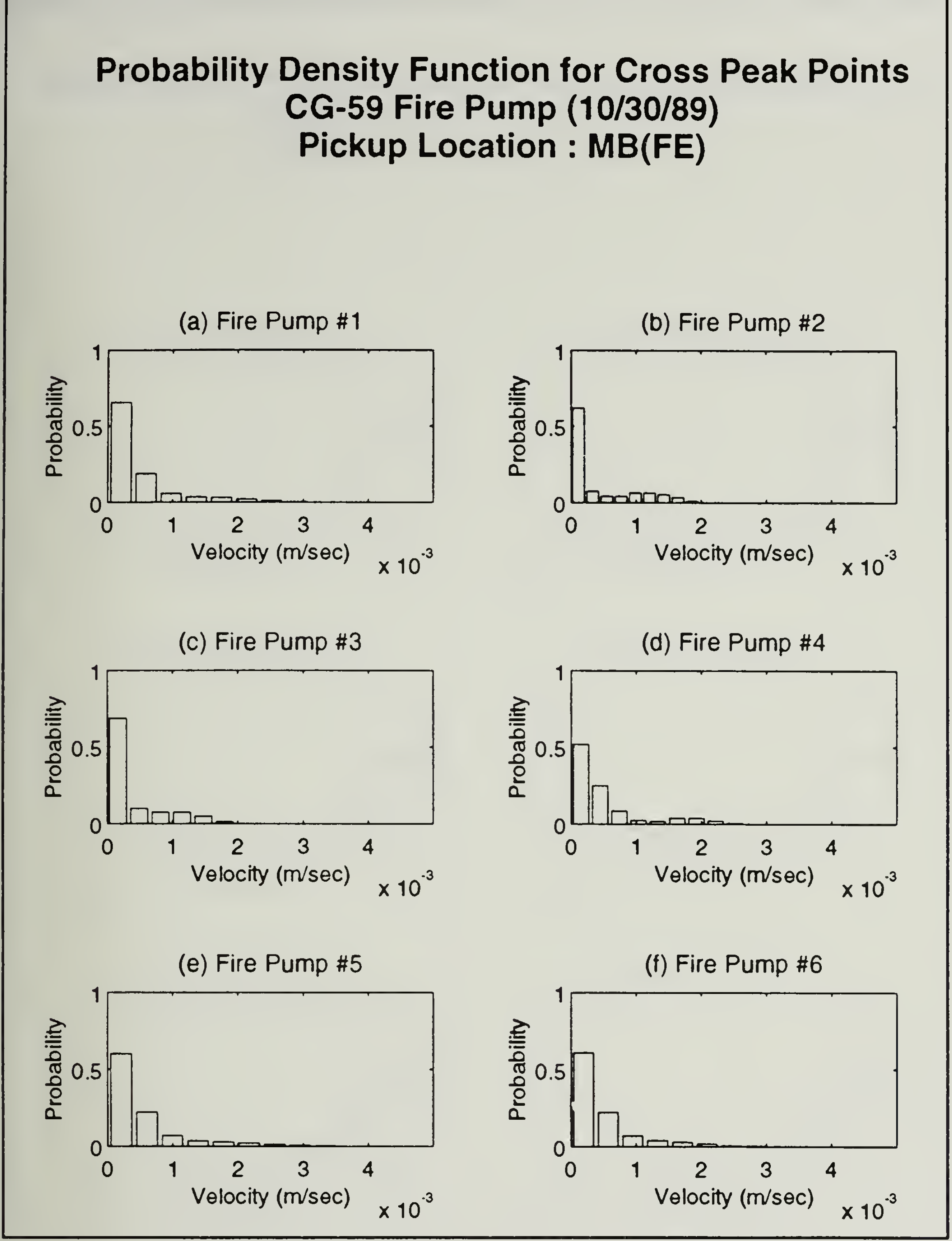


Figure C.1 The Probability Distributions of Cross Peak Data for CG-59(10/30/89) Fire Pumps Measured at MB(FE)

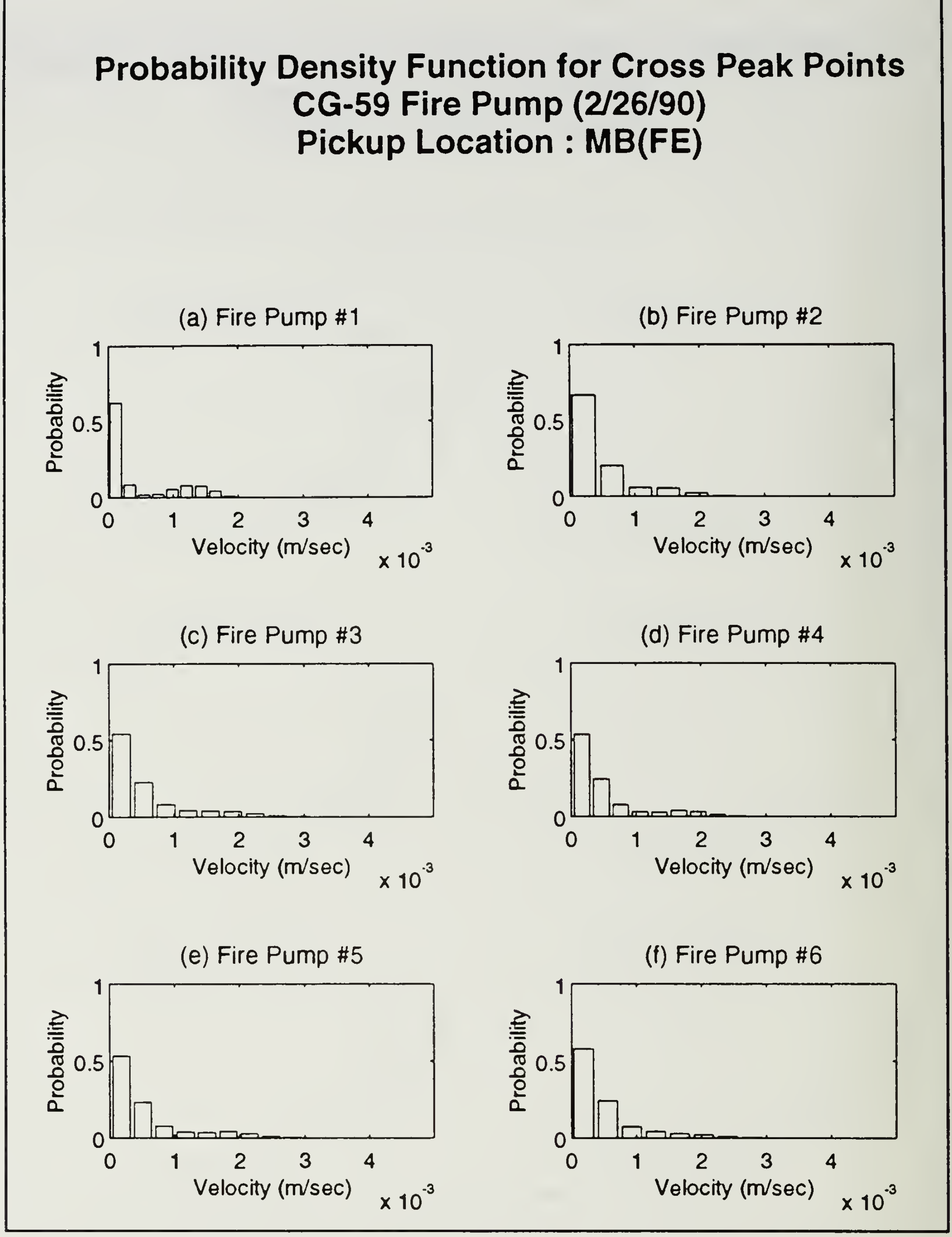


Figure C.2 The Probability Distributions of Cross Peak Data for CG-59 (2/26/90) Fire Pumps Measured at MB(FE)

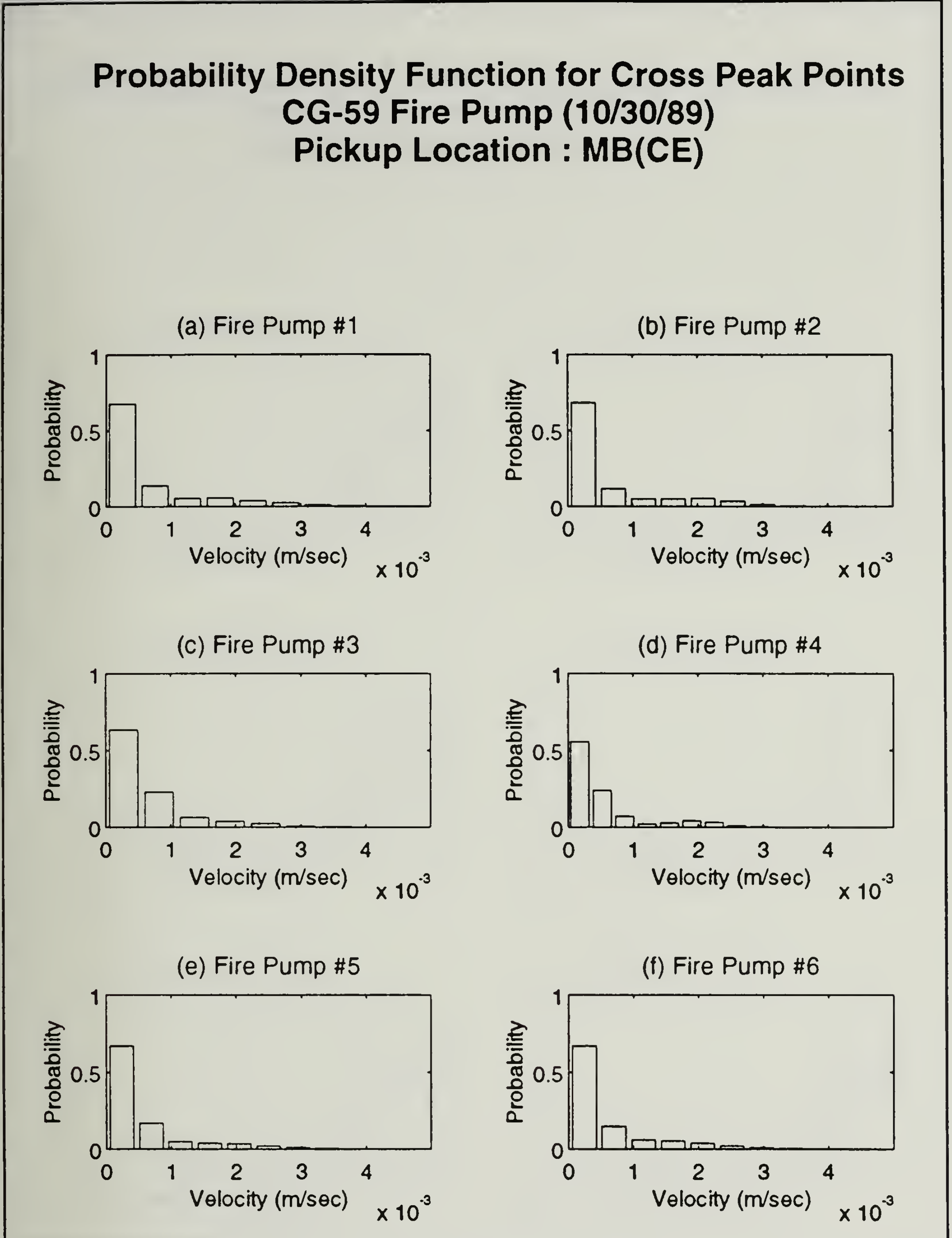


Figure C.3 The Probability Distributions of Cross Peak Data for CG-59(10/30/89) Fire Pumps Measured at MB(CE)

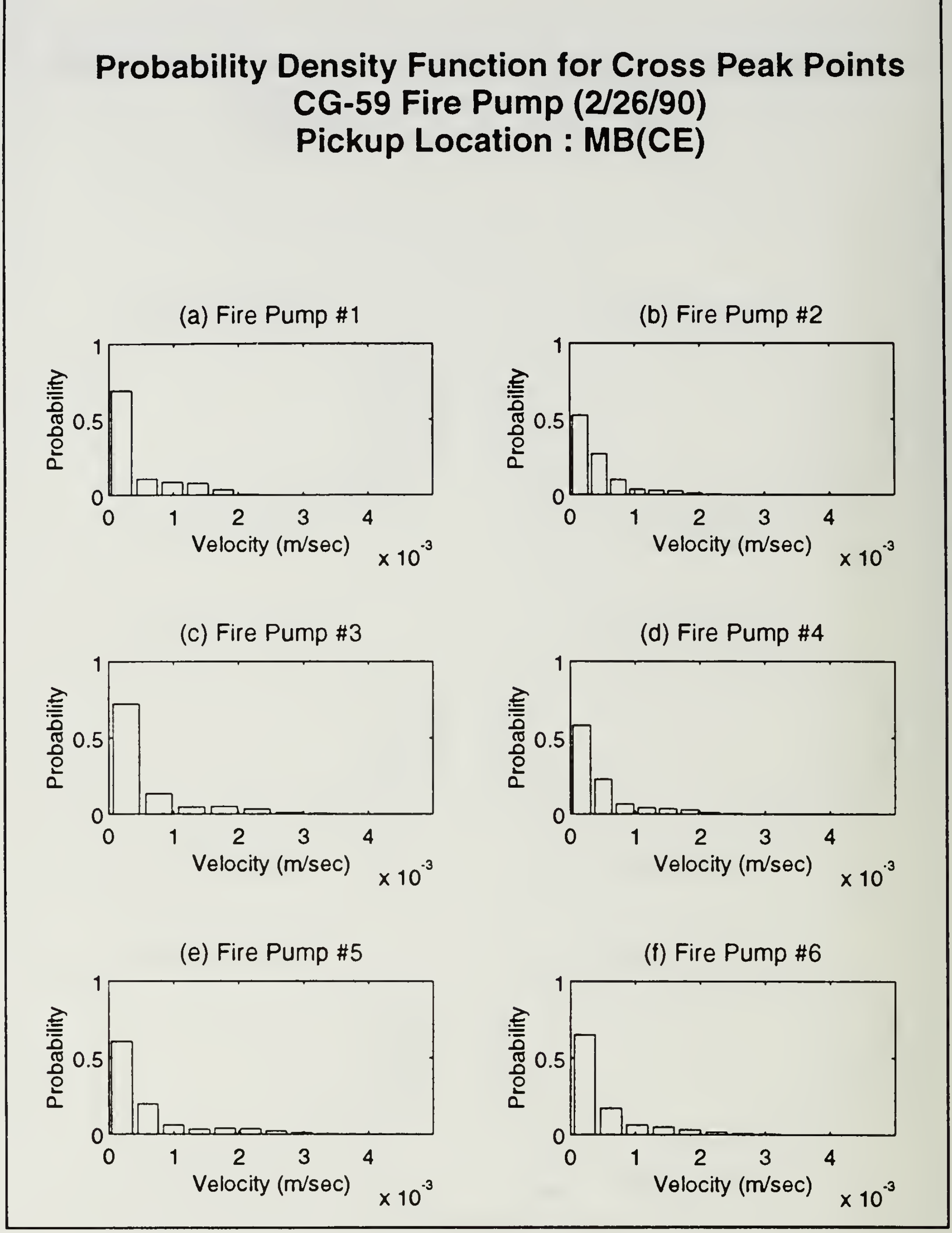


Figure C.4 The Probability Distributions of Cross Peak Data for CG-59 (2/26/90) Fire Pumps Measured at MB(CE)

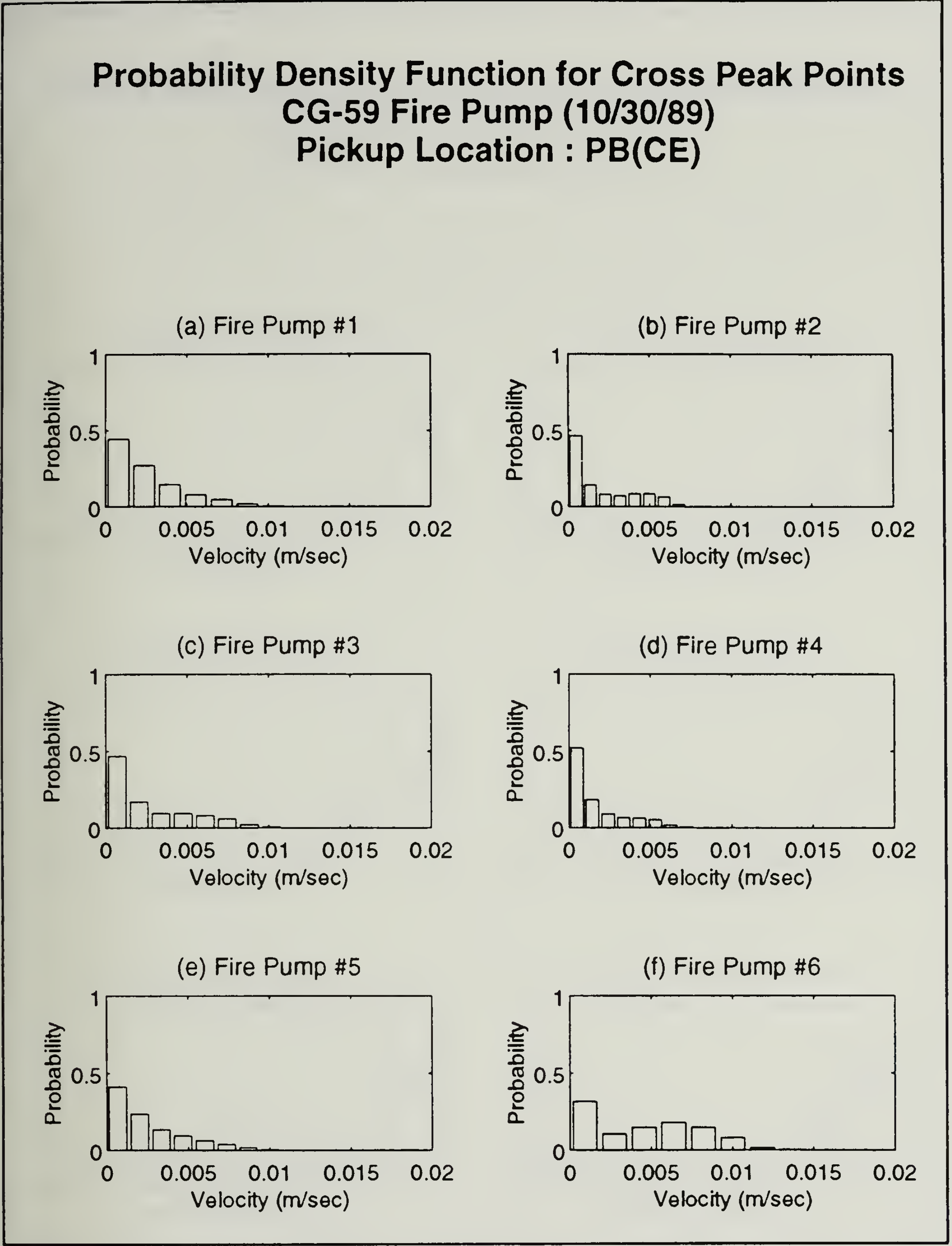


Figure C.5 The Probability Distributions of Cross Peak Data for CG-59(10/30/89) Fire Pumps Measured at PB(CE)

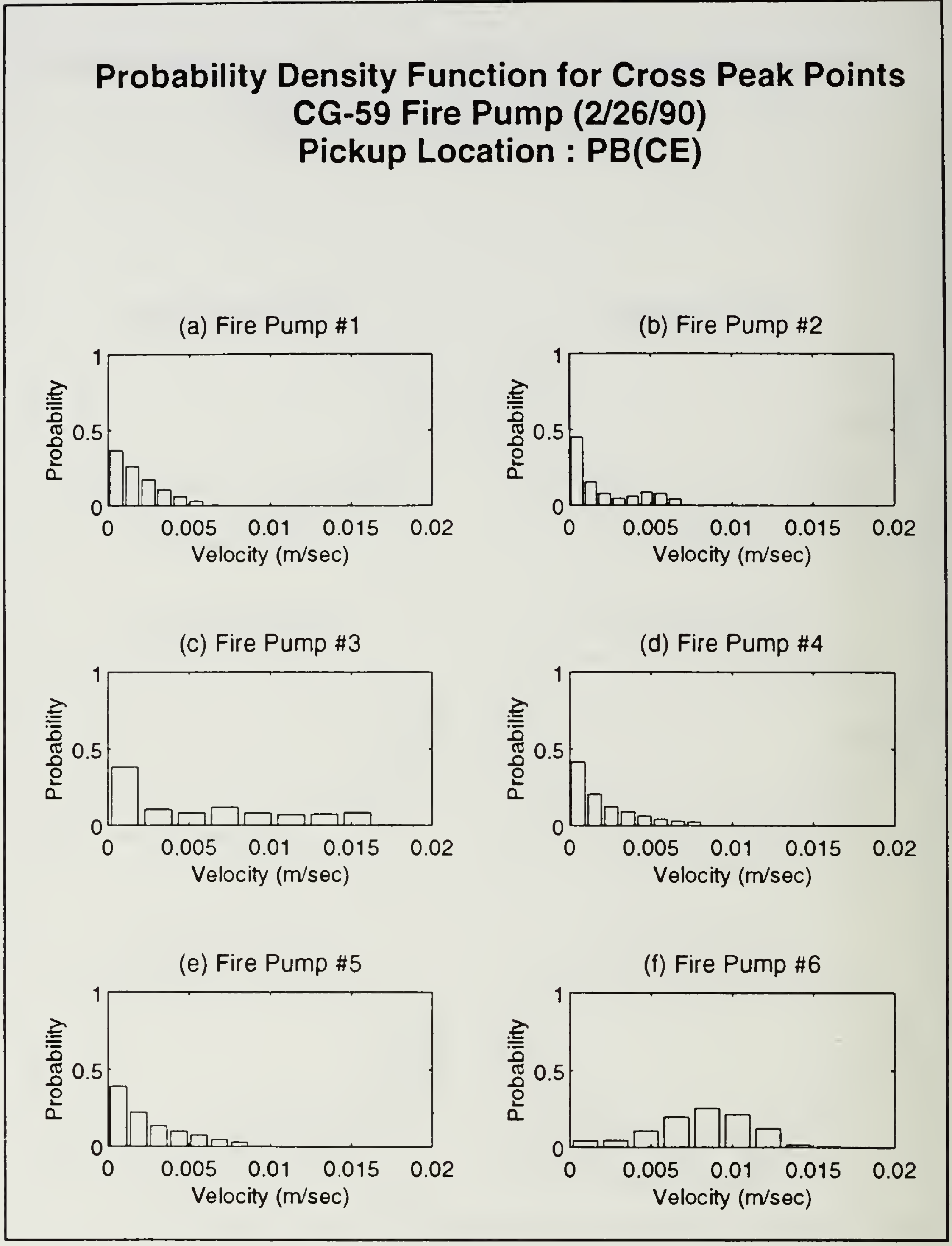


Figure C.6 The Probability Distributions of Cross Peak Data for CG-59 (2/26/90) Fire Pumps Measured at PB(CE)

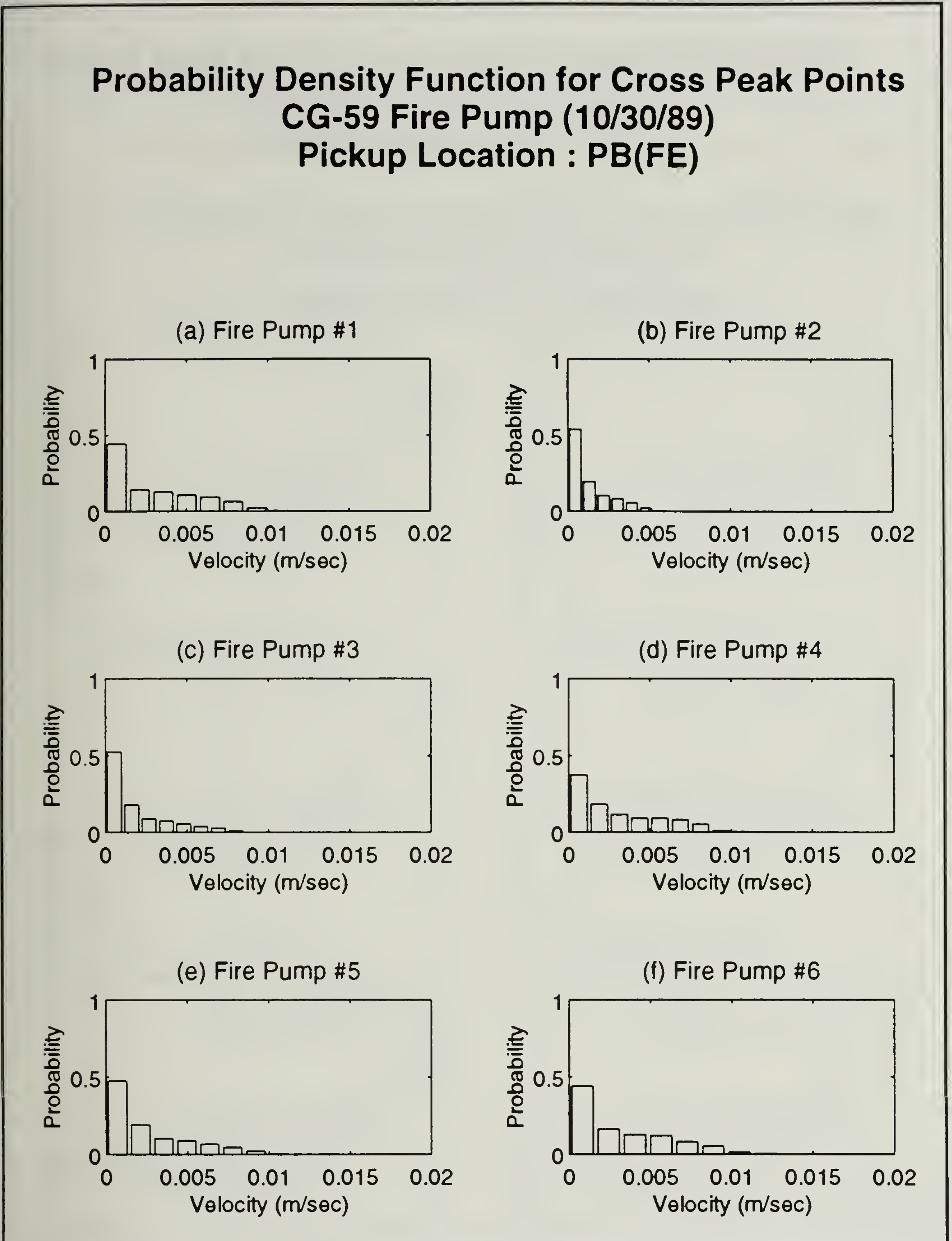


Figure C.7 The Probability Distributions of Cross Peak Data for CG-59(10/30/89) Fire Pumps Measured at PB(FE)

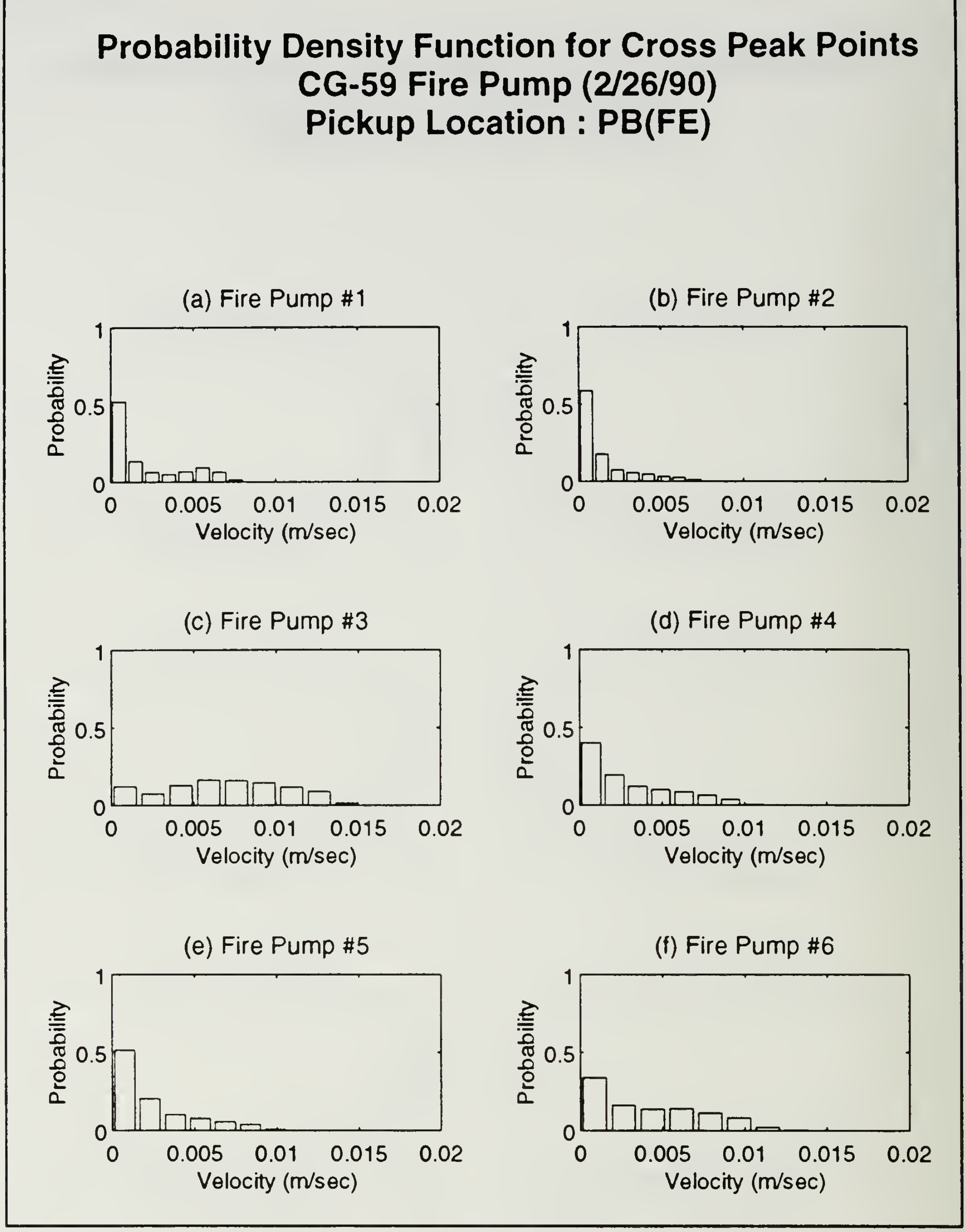


Figure C.8 The Probability Distributions of Cross Peak Data for CG-59 (2/26/90) Fire Pumps Measured at PB(FE)

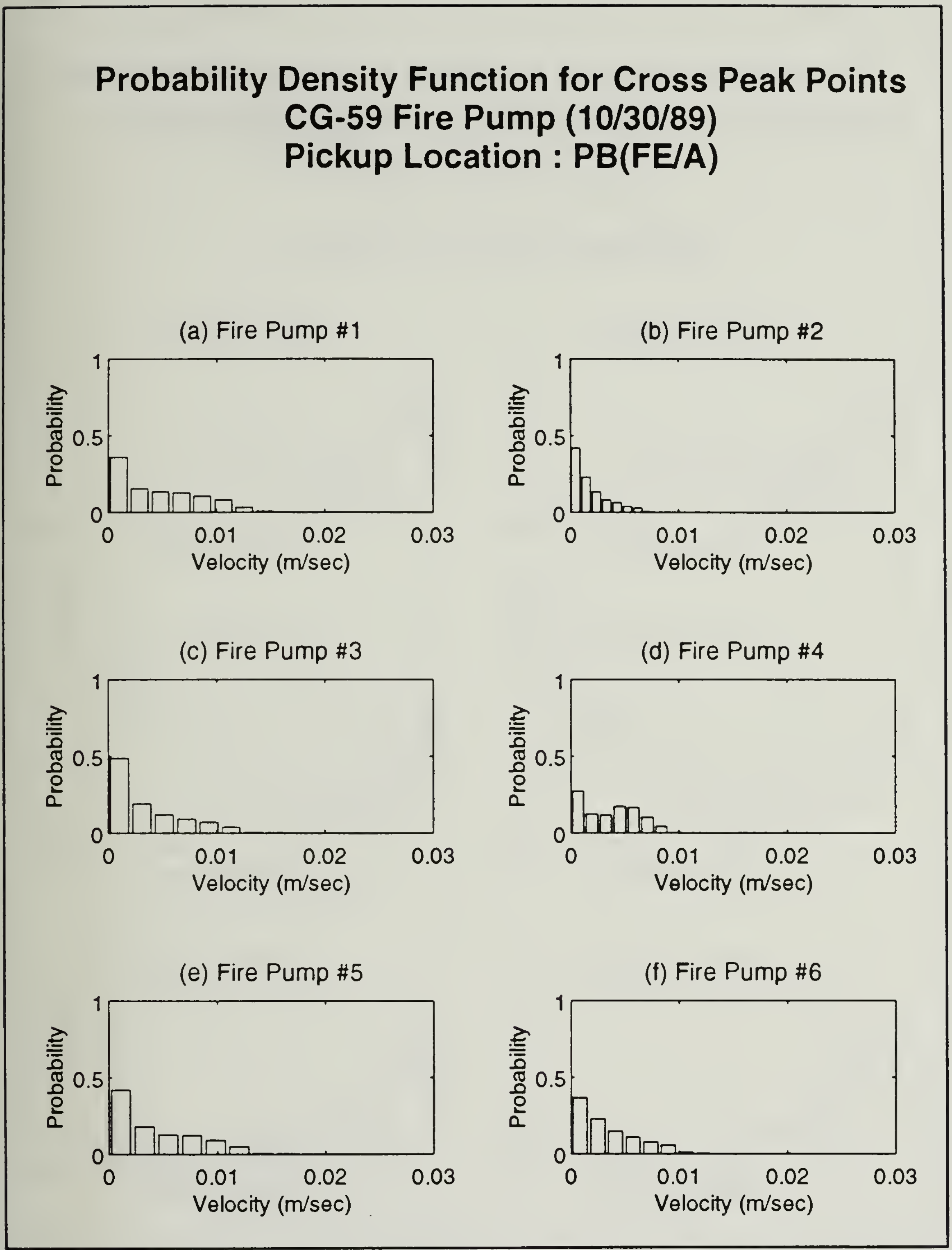


Figure C.9 The Probability Distributions of Cross Peak Data for CG-59(10/30/89) Fire Pumps Measured at PB(FE/A)

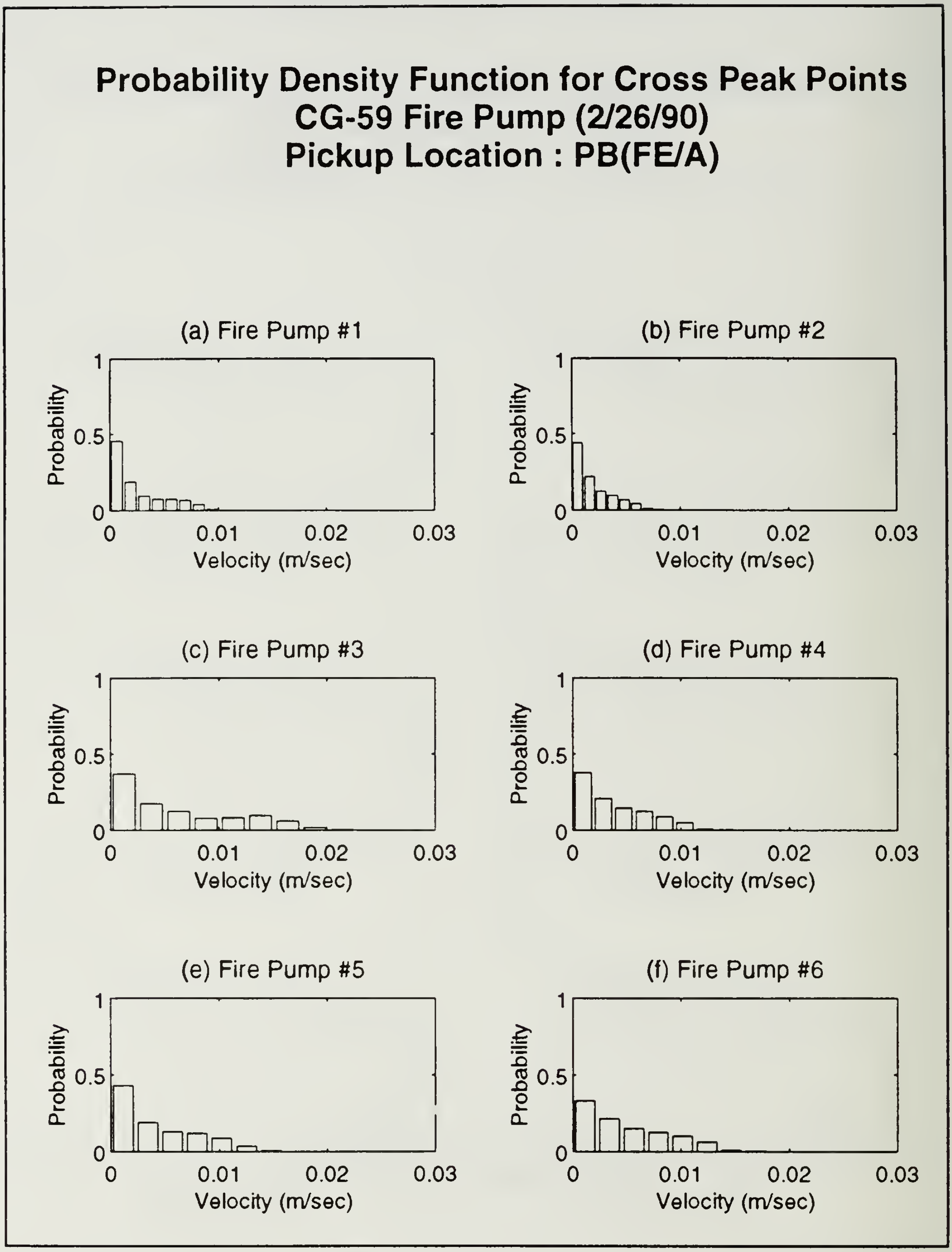


Figure C.10 The Probability Distributions of Cross Peak Data for CG-59 (2/26/90) Fire Pumps Measured at PB(FE/A)

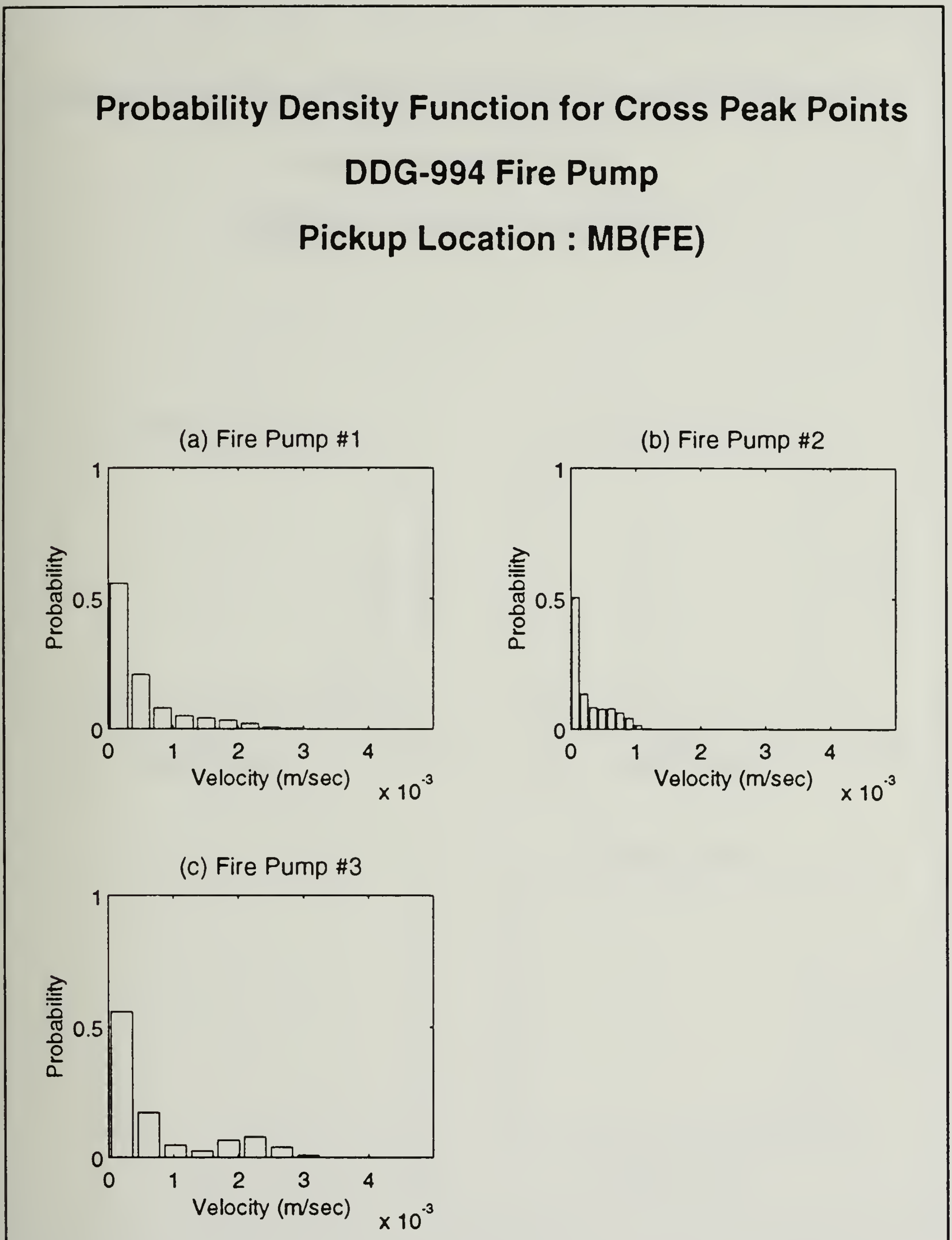


Figure C.11 The Probability Distributions of Cross Peak Data for DDG-994 Fire Pumps Measured at MB(FE)

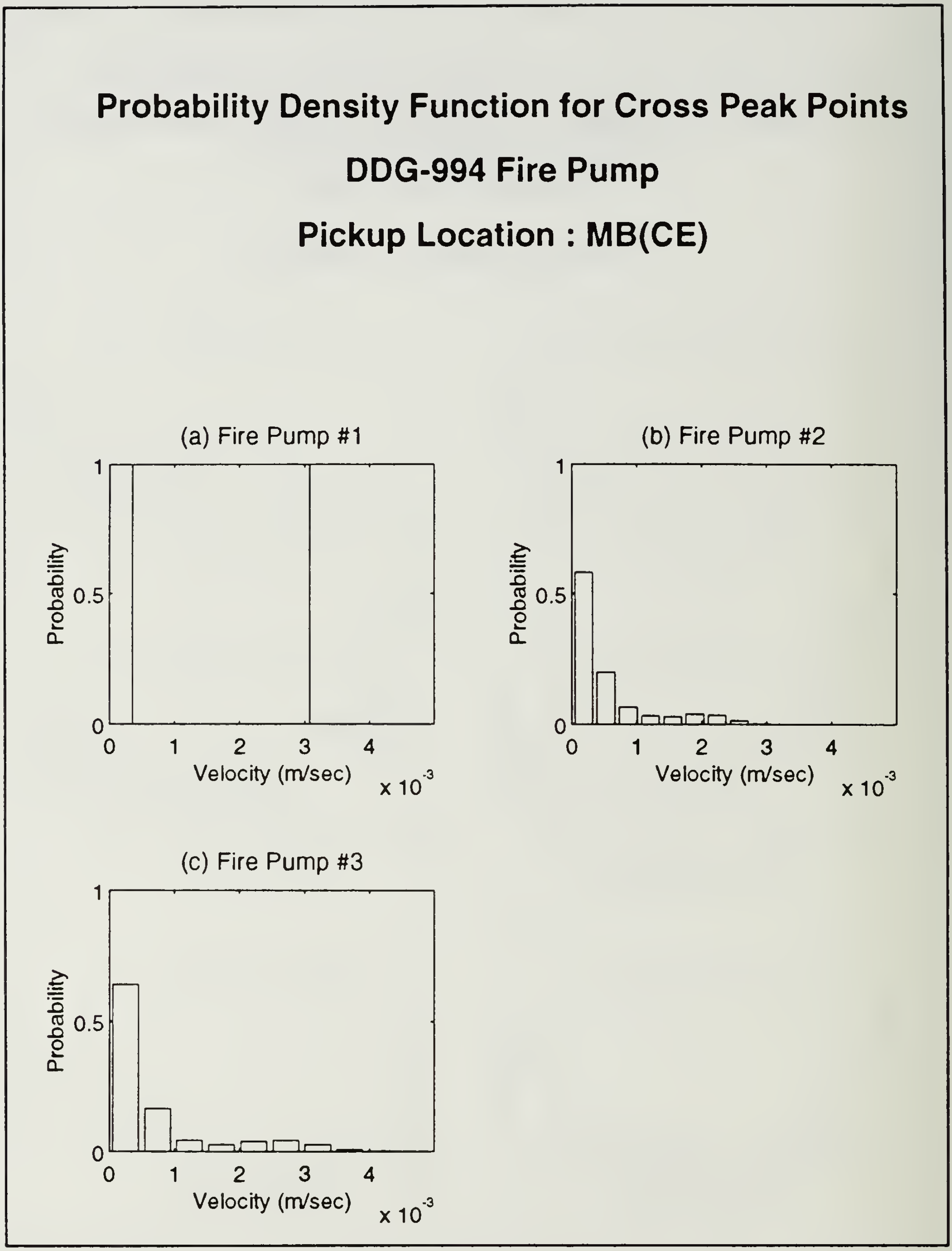


Figure C.12 The Probability Distributions of Cross Peak Data for DDG-994 Fire Pumps Measured at MB(CE)

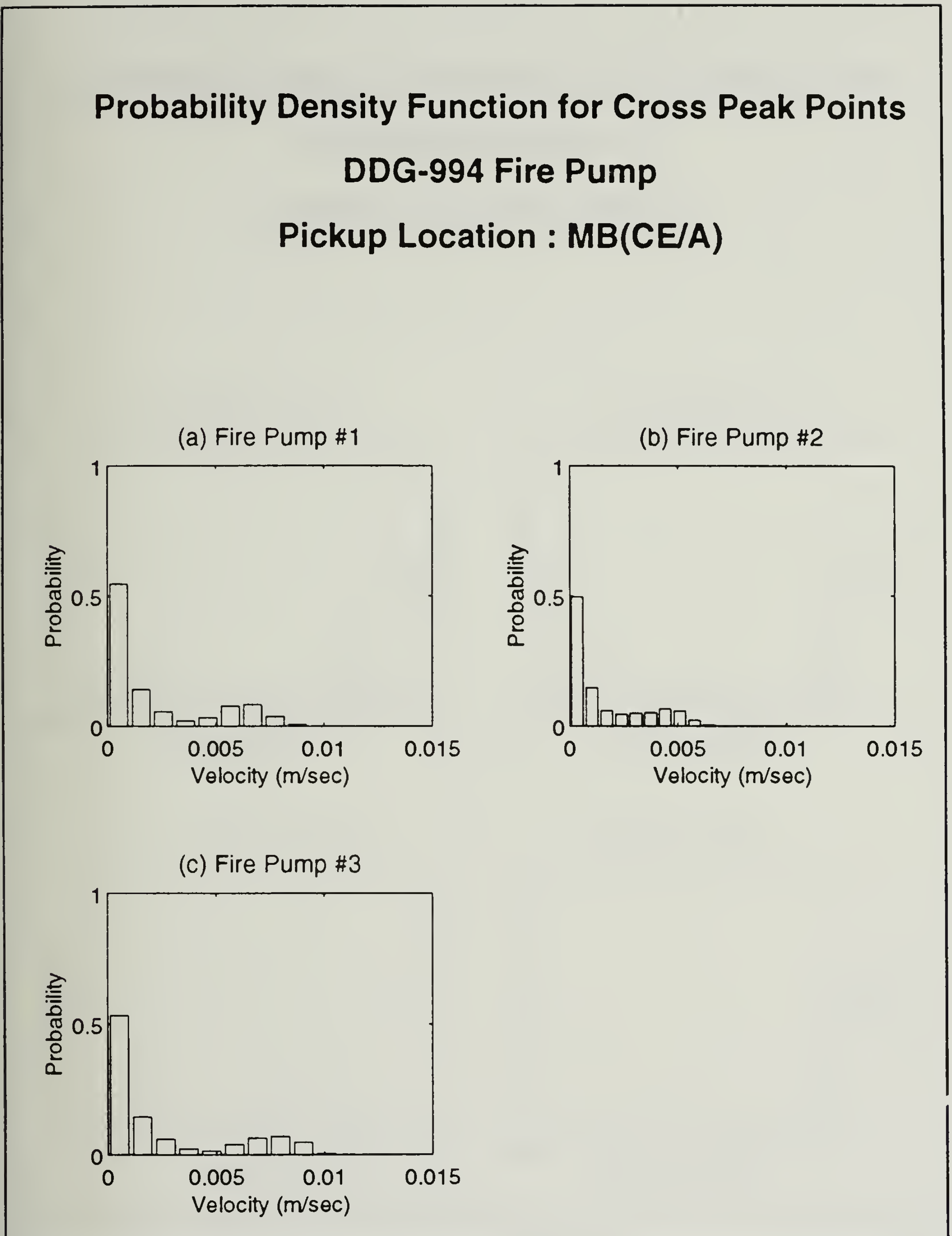


Figure C.13 The Probability Distributions of Cross Peak Data for DDG-994

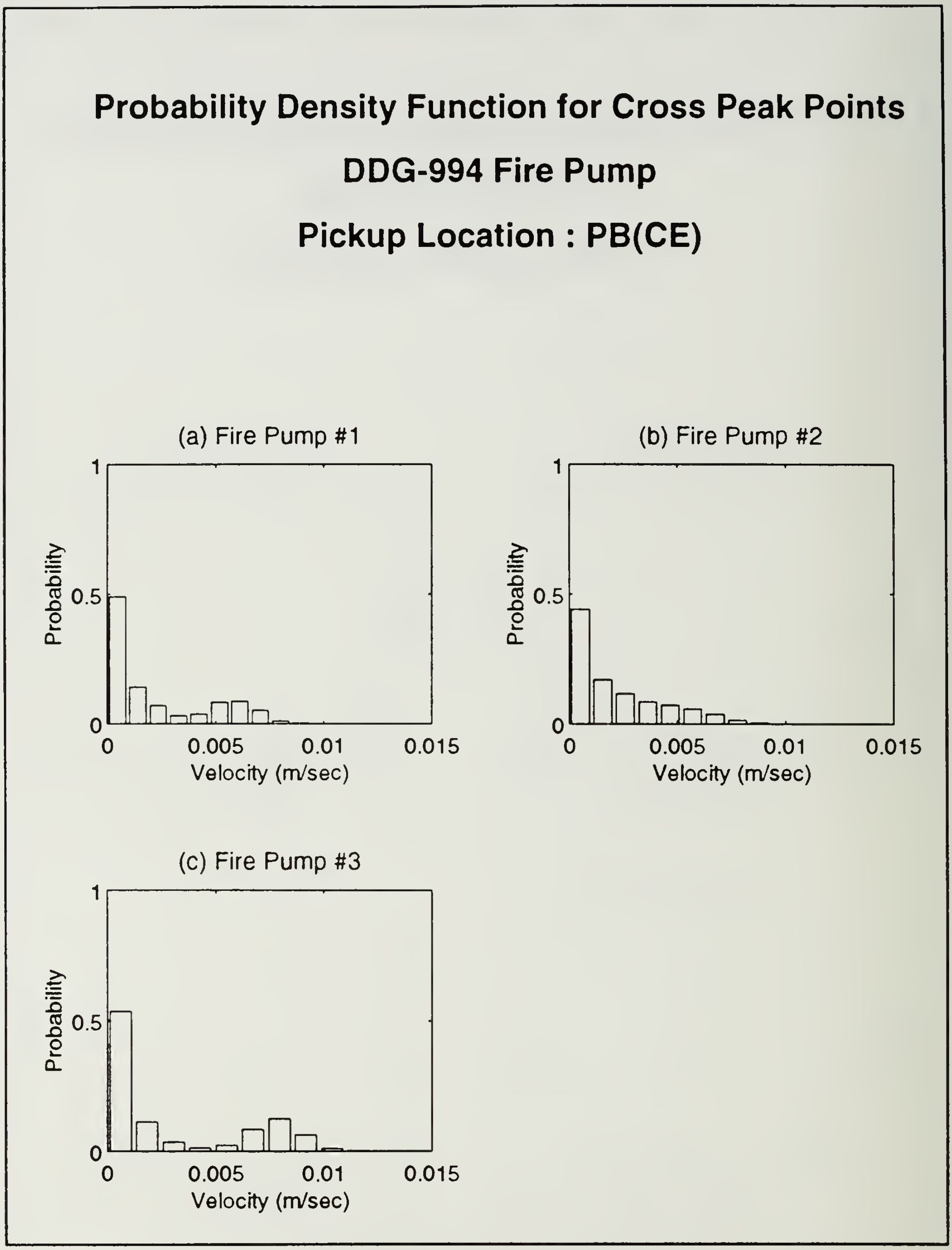


Figure C.14 The Probability Distributions of Cross Peak Data for DDG-994 Fire Pumps Measured at PB(CE)

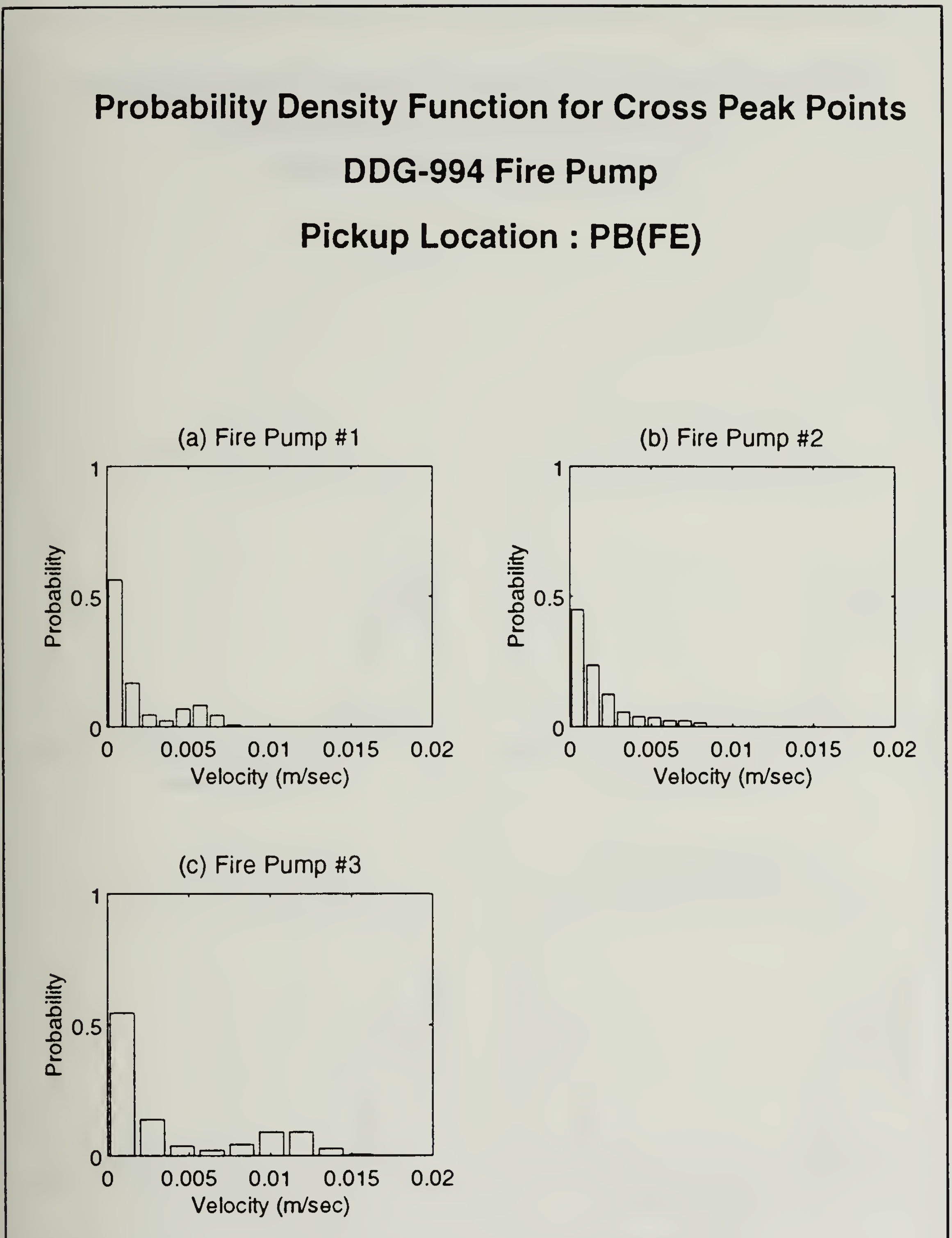


Figure C.15 The Probability Distributions of Cross Peak Data for DDG-994 Fire Pumps Measured at PB(FE)

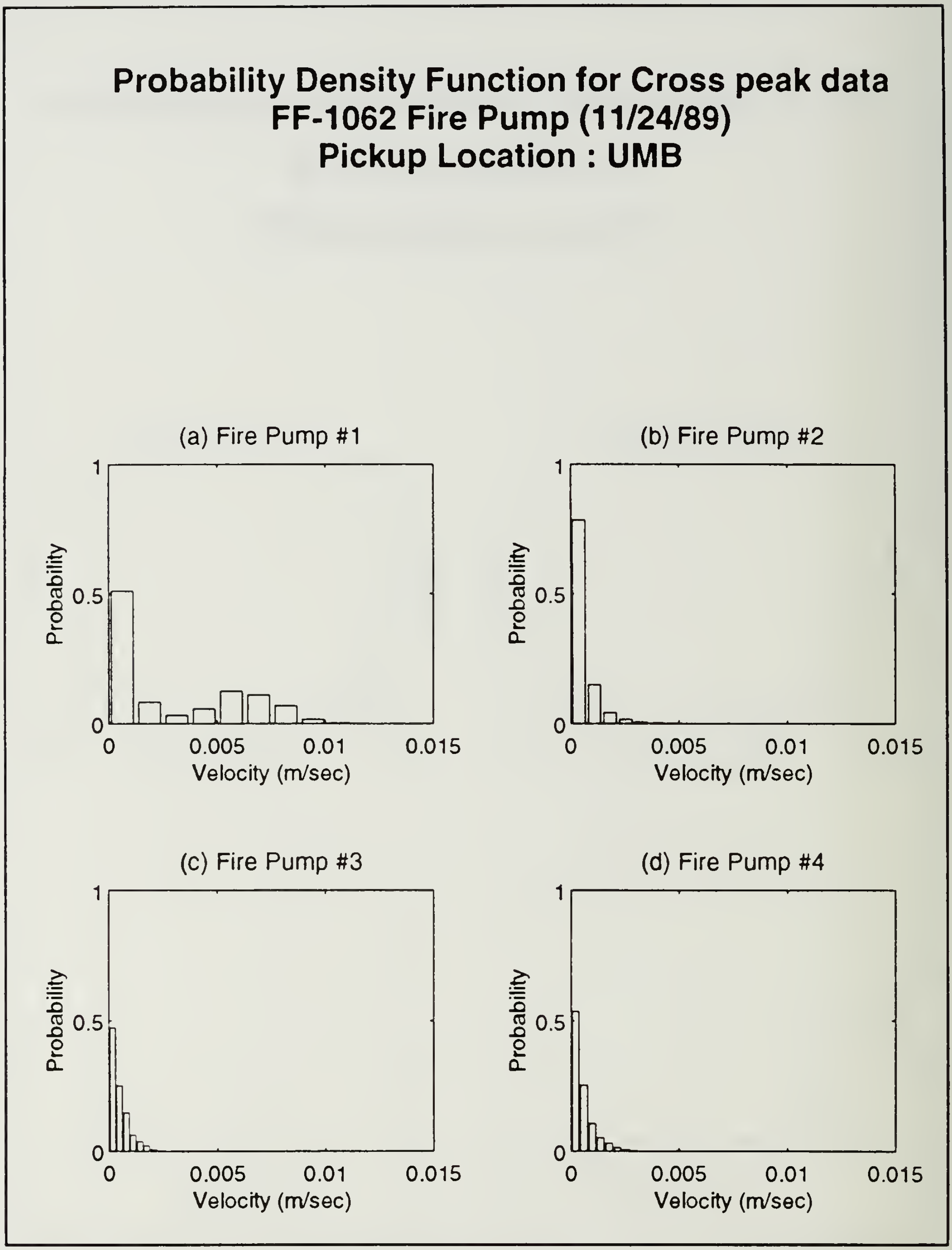


Figure C.16 The Probability Distributions of Cross Peak Data for FF-1062 Fire Pumps Measured at UMB

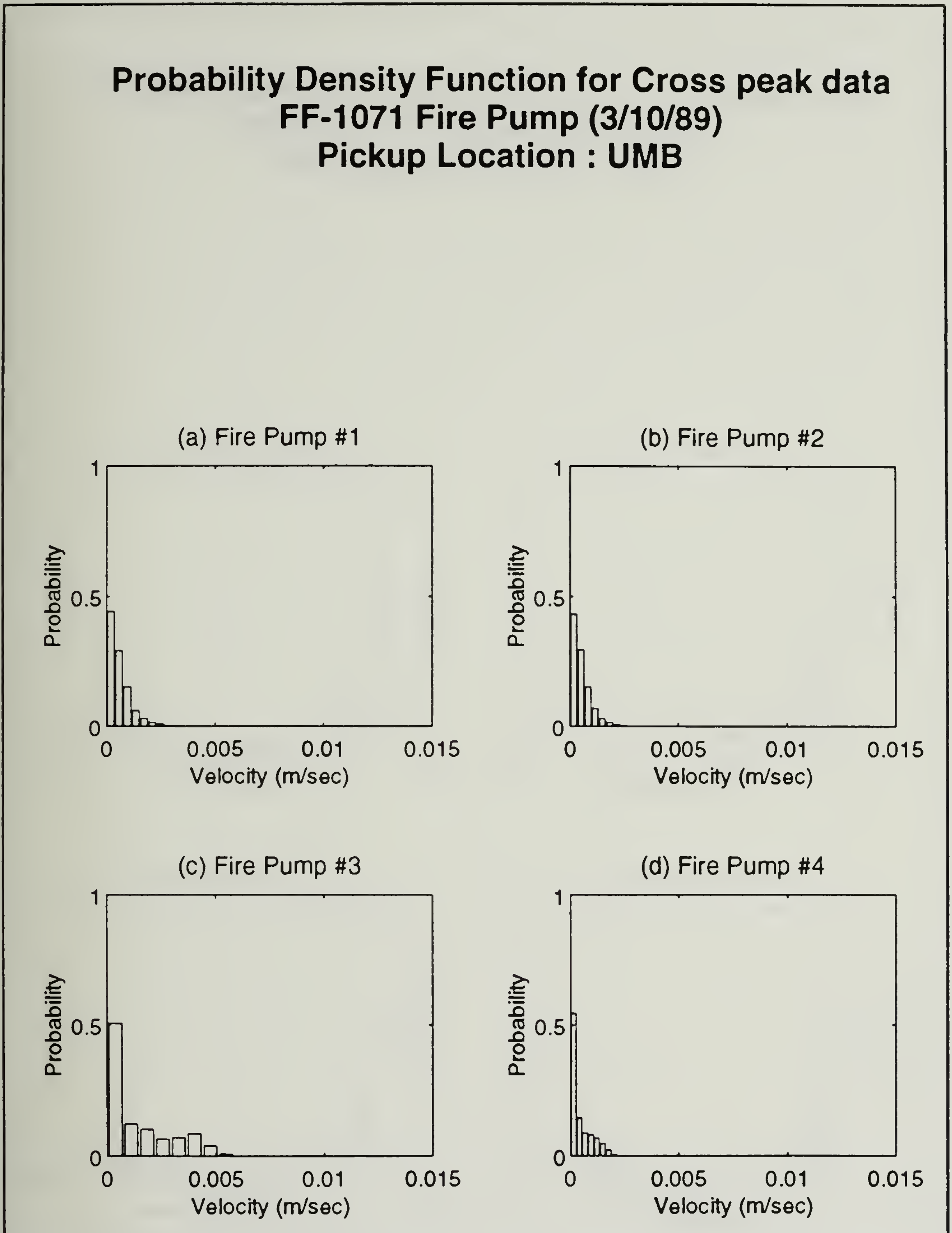


Figure C.17 The Probability Distributions of Cross Peak Data for FF-1071 Fire Pumps Measured at UMB

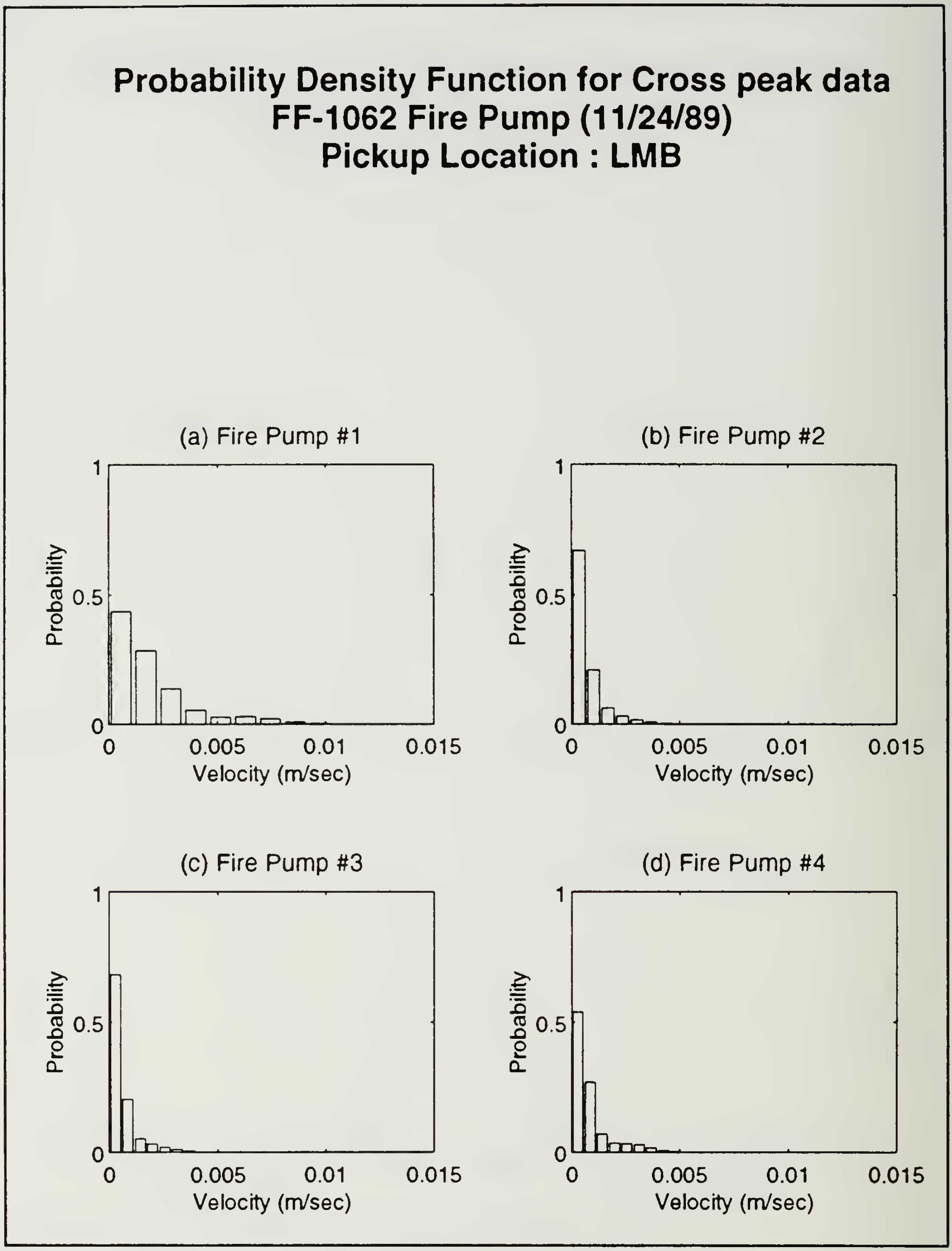


Figure C.18 The Probability Distributions of Cross Peak Data for FF-1062 Fire Pumps Measured at LMB

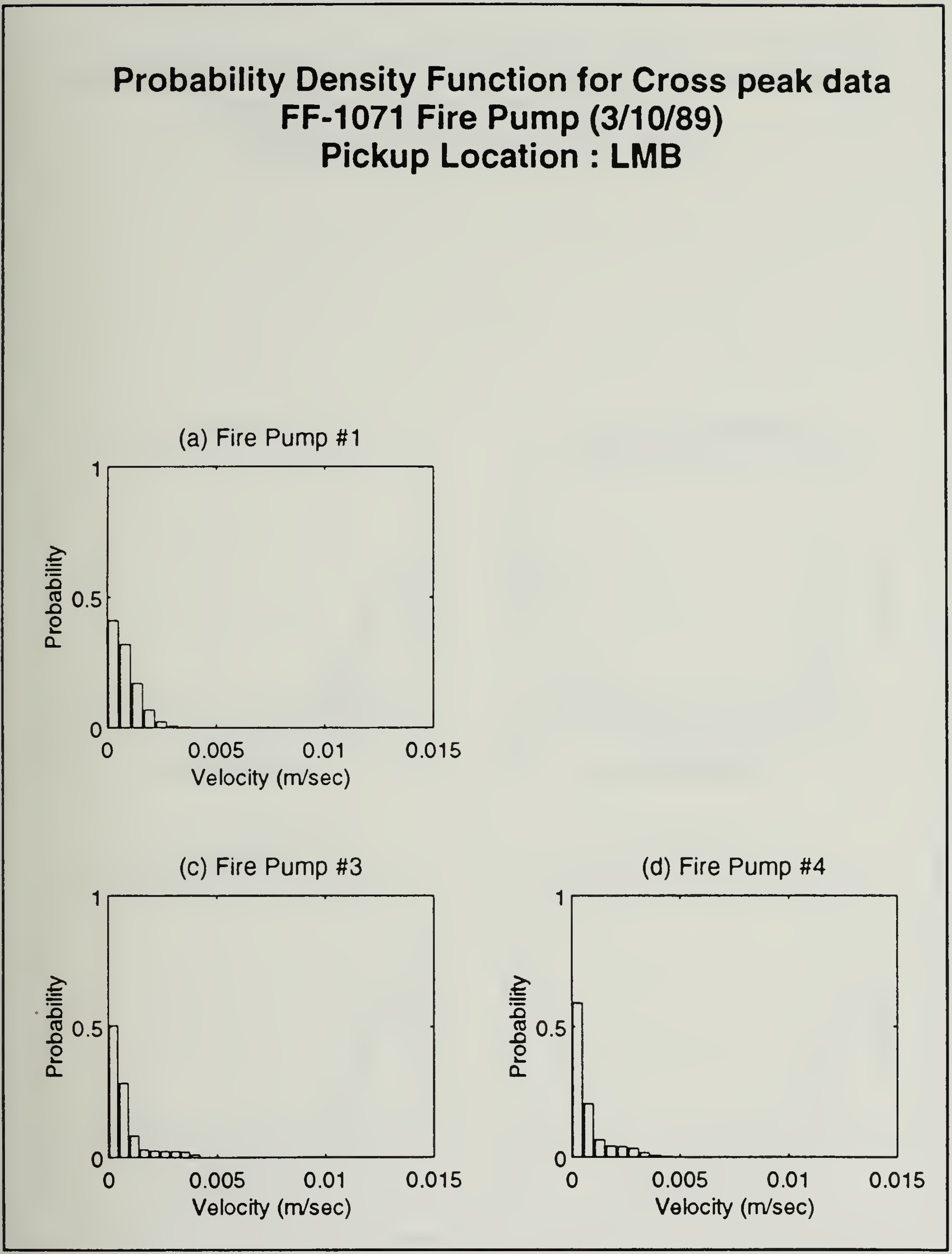


Figure C.19 The Probability Distributions of Cross Peak Data for FF-1071 Fire Pumps Measured at LMB

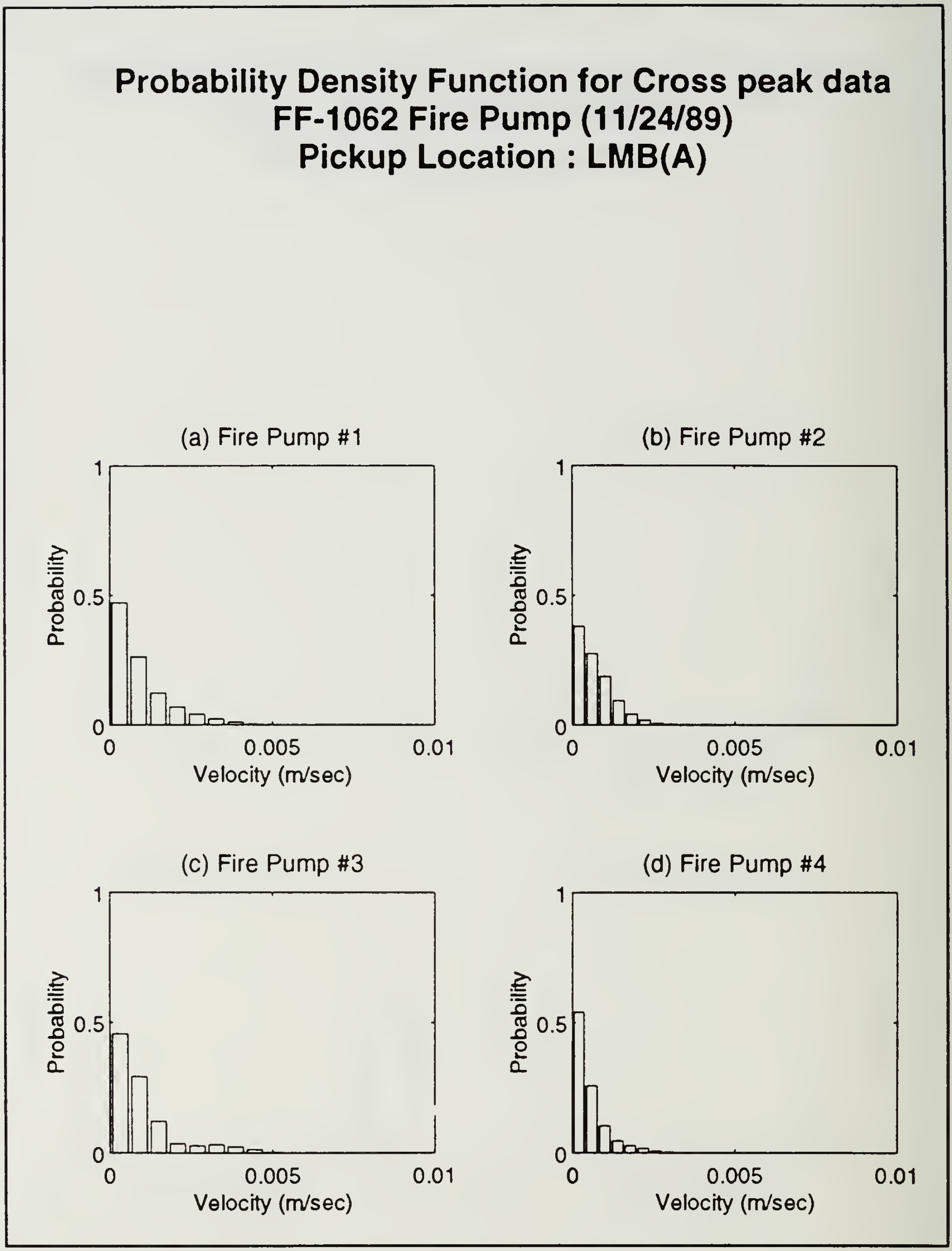


Figure C.20 The Probability Distributions of Cross Peak Data for FF-1062 Fire Pumps Measured at LMB(A)

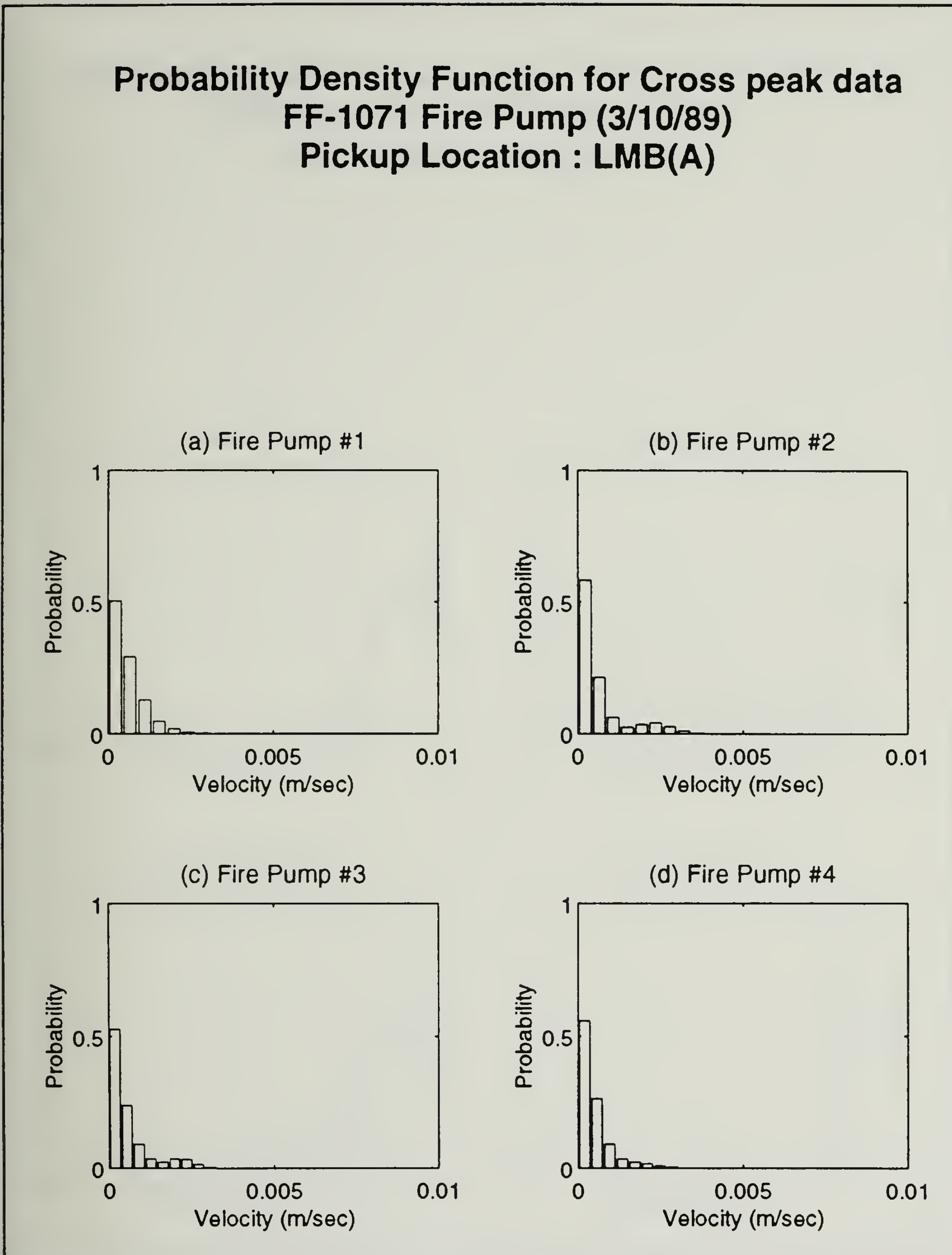


Figure C.21 The Probability Distributions of Cross Peak Data for FF-1071 Fire Pumps Measured at LMB(A)

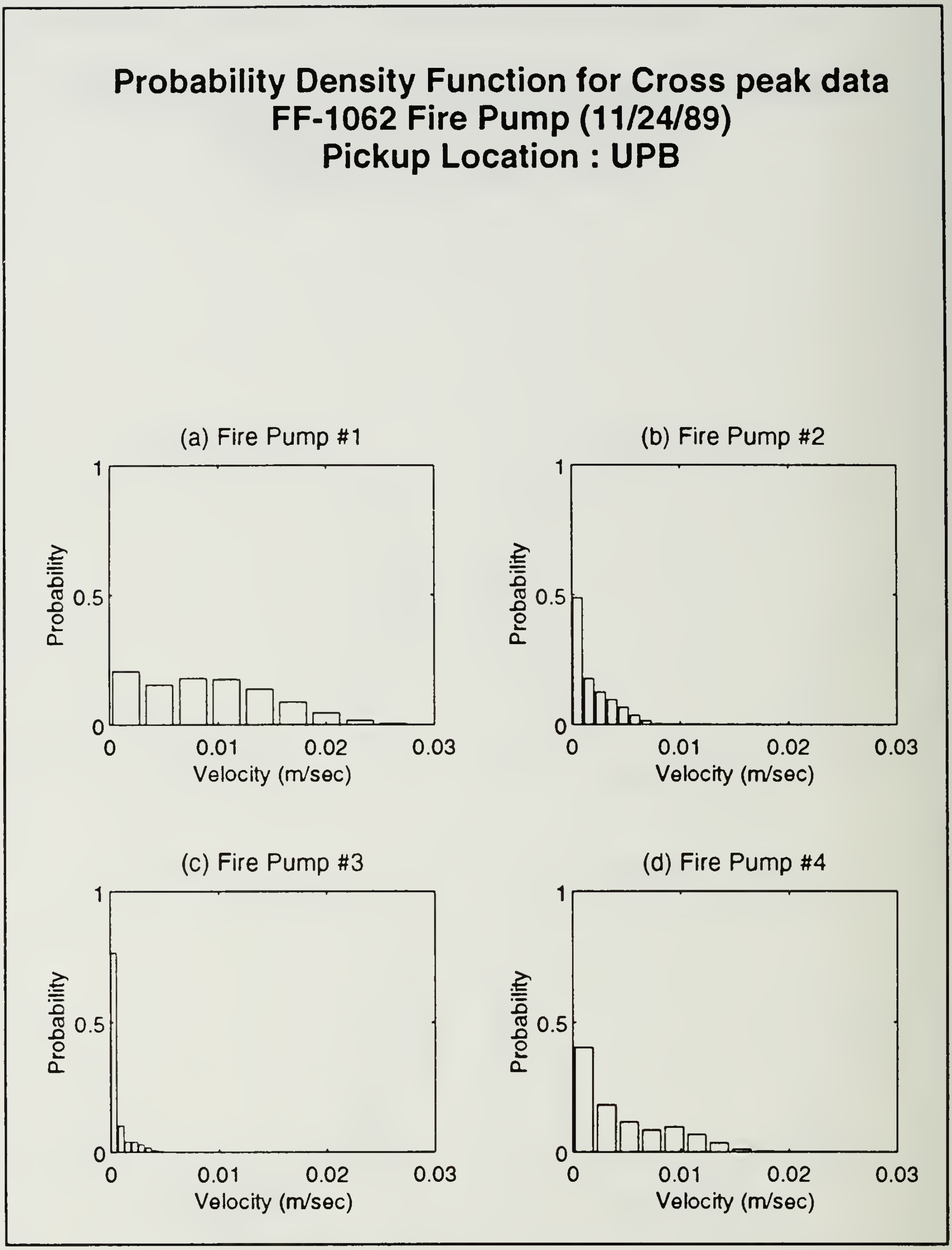


Figure C.22 The Probability Distributions of Cross Peak Data for FF-1062 Fire Pumps Measured at UPB

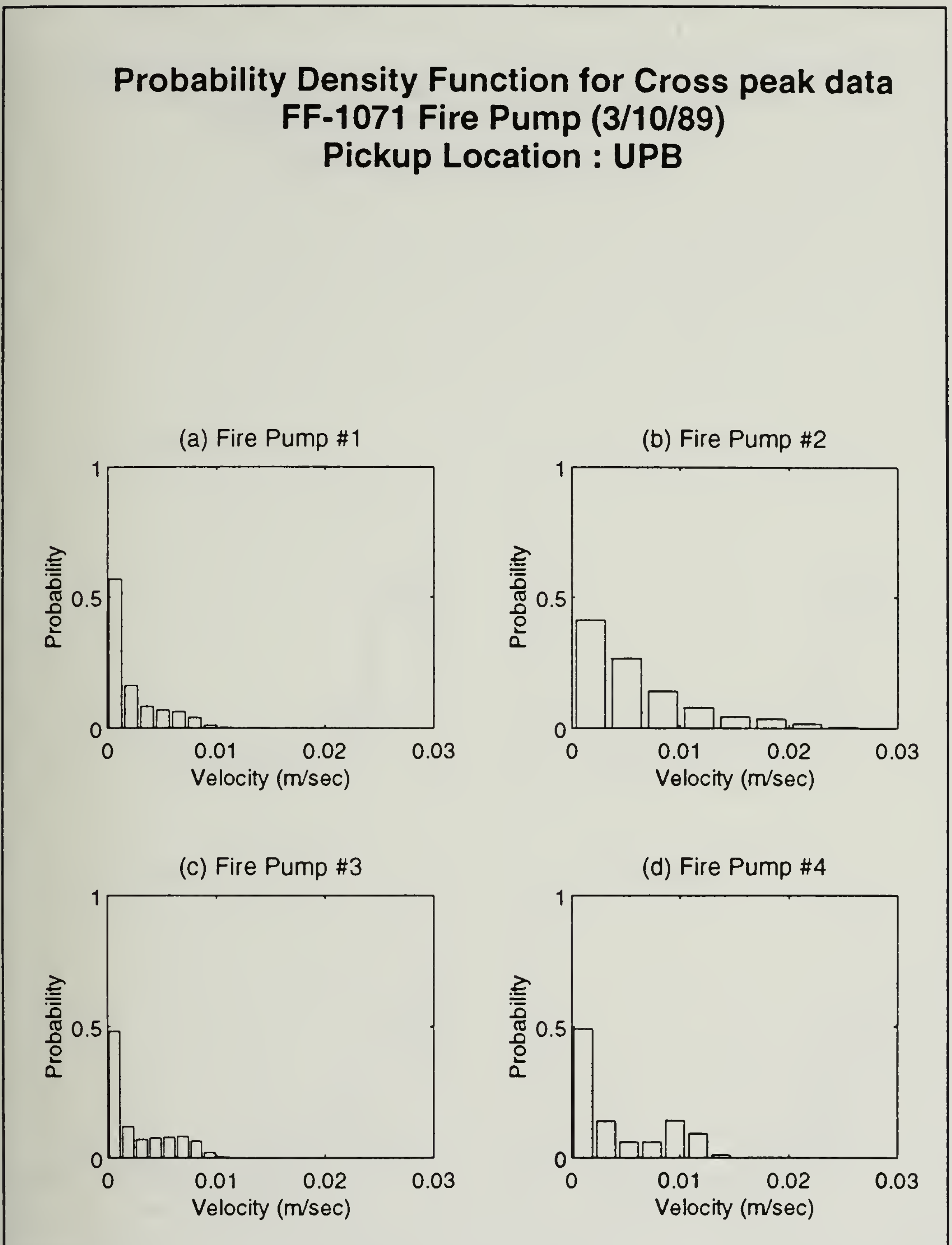


Figure C.23 The Probability Distributions of Cross Peak Data for FF-1071 Fire Pumps Measured at UPB

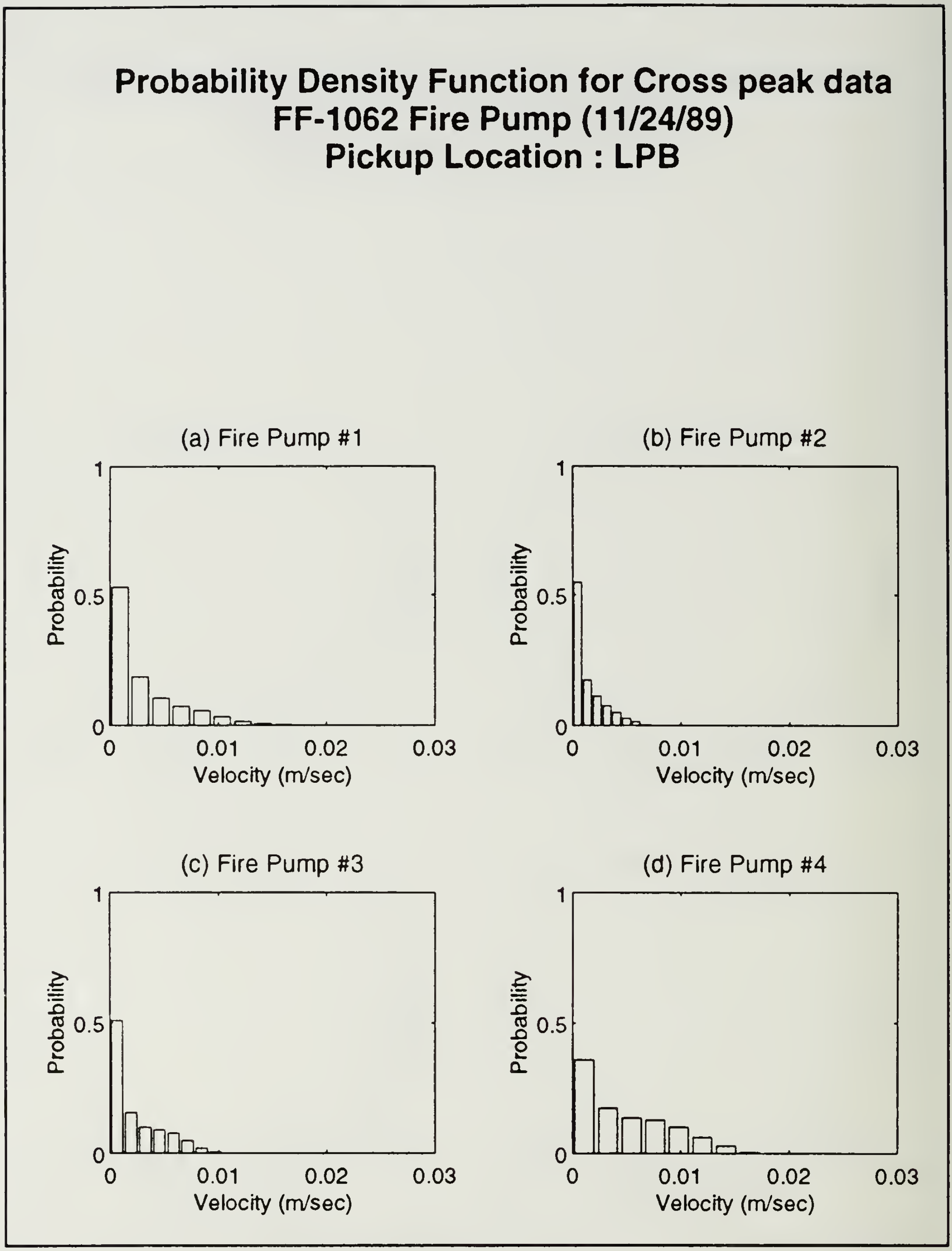


Figure C.24 The Probability Distributions of Cross Peak Data for FF-1062 Fire Pumps Measured at LPB

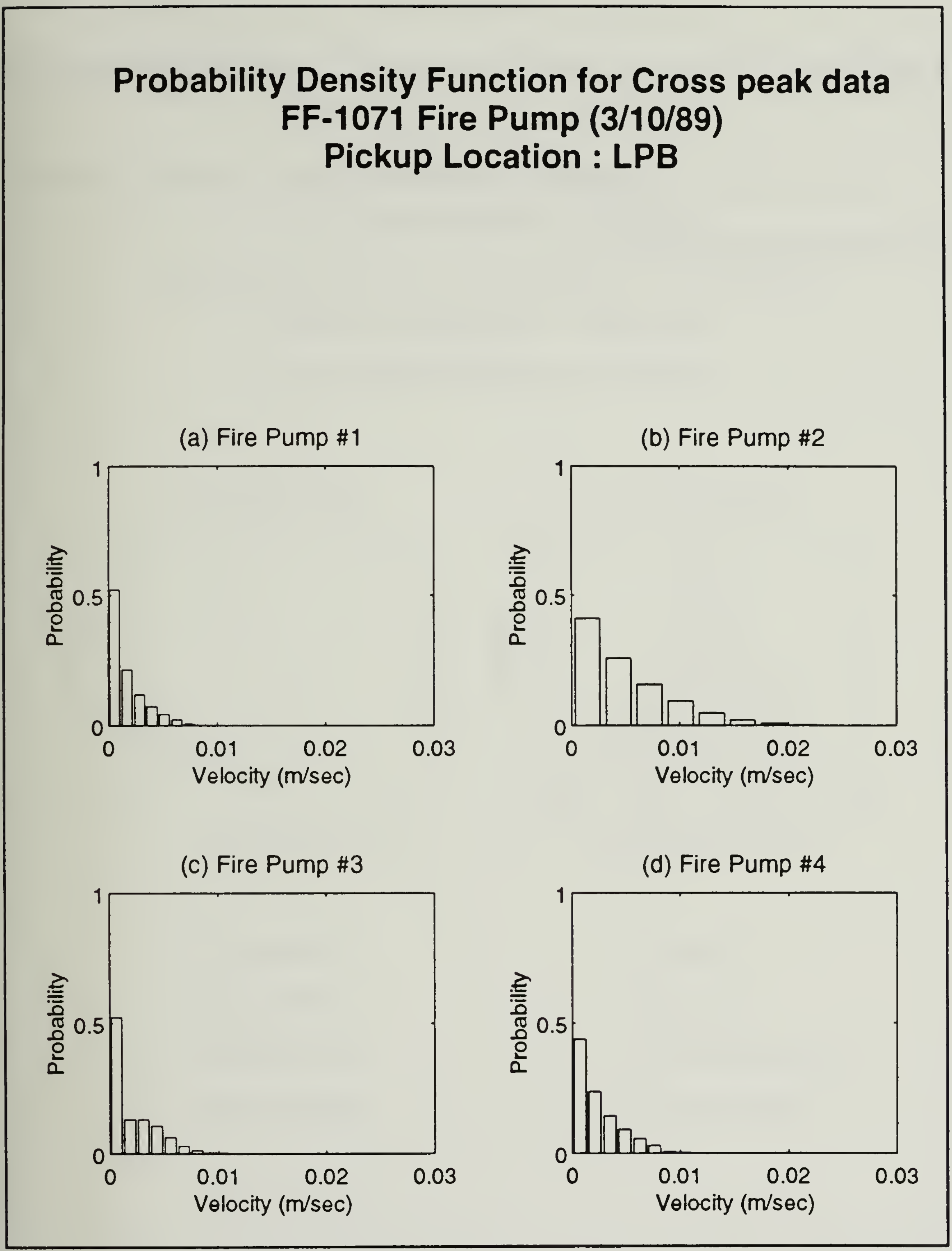


Figure C.25 The Probability Distributions of Cross Peak Data for FF-1071 Fire Pumps Measured at LPB

APPENDIX D. FIGURES OF STATISTICAL ANALYSIS RESULTS

This section contains figures of the statistical analysis results with and without considering damaged data sets.

Statistical Analysis Results

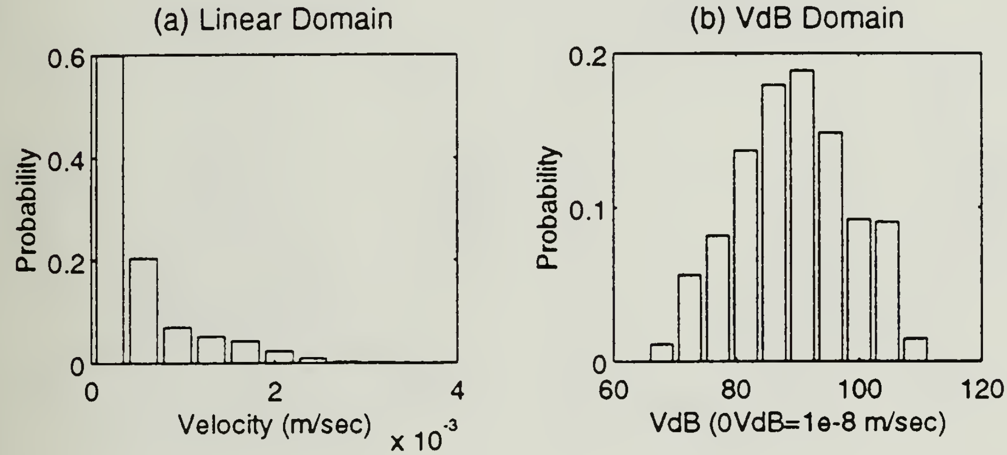
CG-59 Fire Pump

Pickup Location : MB(FE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 1.965e+005

The sampling frequency : 1e+004 Hz



(a)	(b)
μ=0.0004954	μ = 89.36
σ=0.0005325	σ = 9.203
Skewness=1.85	*Skewness=-0.04575*
Kurtosis=6.201	*Kurtosis=2.378*

Figure D.1 The Statistical Analysis Results for Type I Fire Pumps Measured at MB(FE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

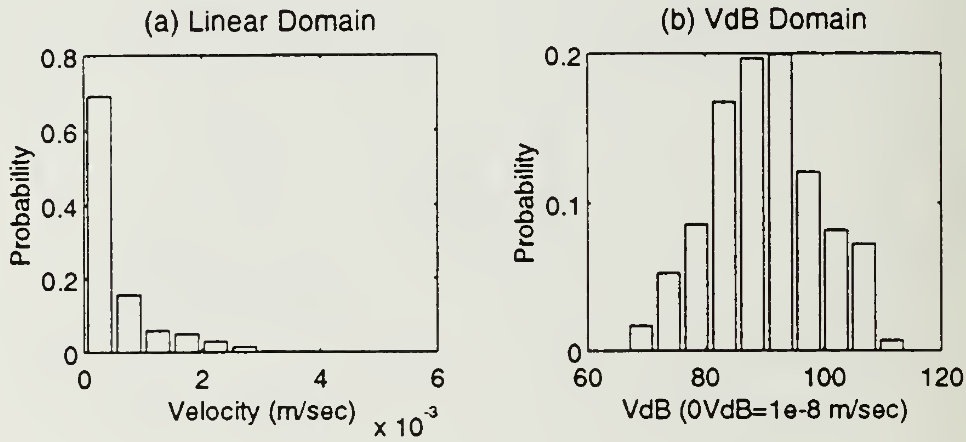
CG-59 Fire Pump

Pickup Location : MB(CE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 2.173e+005

The sampling frequency : 1e+004 Hz



μ=0.0005393	μ = 90.02
σ=0.0006076	σ = 9.121
Skewness=2.052	*Skewness=0.04893*
Kurtosis=7.195	*Kurtosis=2.444*

Figure D.2 The Statistical Analysis Results for Type I Fire Pumps Measured at MB(CE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

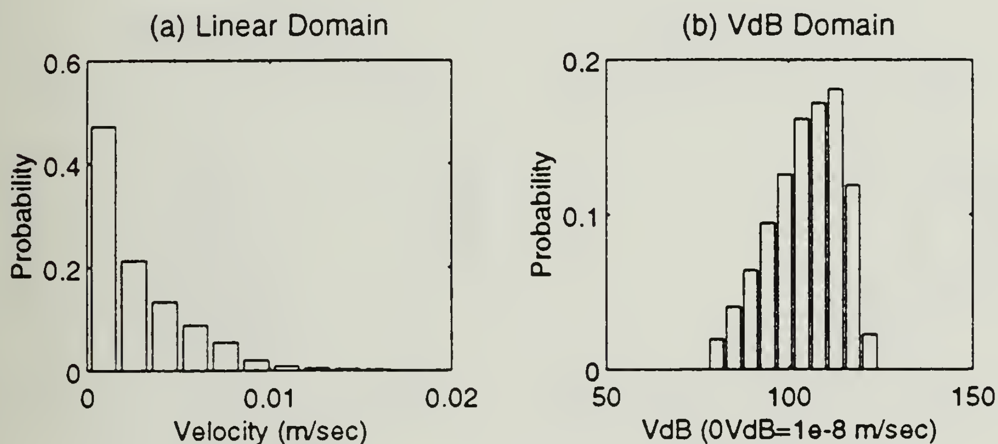
CG-59 Fire Pump

Pickup Location : PB(CE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 3.129e+005

The sampling frequency : 1e+004 Hz



μ=0.002828	μ = 104.6
σ=0.00268	σ = 9.775
Skewness=1.517	*Skewness=-0.4436*
Kurtosis=5.638	*Kurtosis=2.476*

Figure D.3 The Statistical Analysis Results for Type I Fire Pumps Measured at PB(CE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

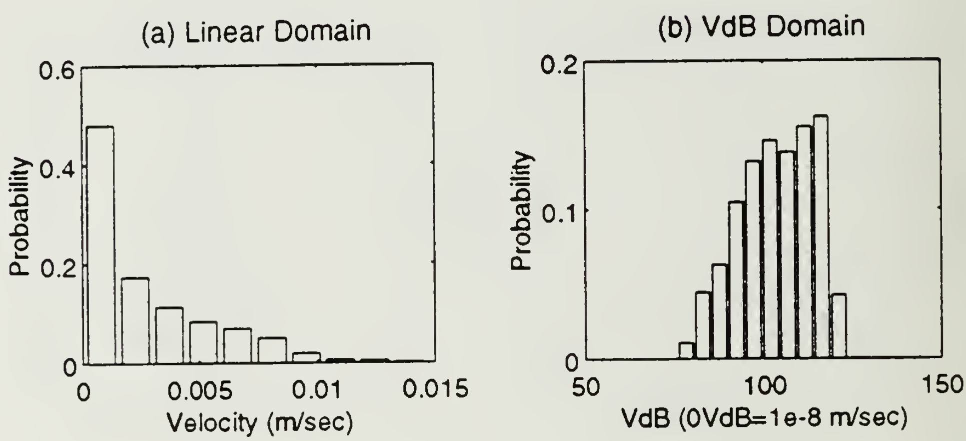
CG-59 Fire Pump

Pickup Location : PB(FE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 2.614e+005

The sampling frequency : 1e+004 Hz



(a)	(b)
μ=0.002717	μ = 103.6
σ=0.002681	σ = 10.45
Skewness=1.253	*Skewness=-0.3354*
Kurtosis=3.959	*Kurtosis=2.232*

Figure D.4 The Statistical Analysis Results for Type I Fire Pumps Measured at PB(FE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

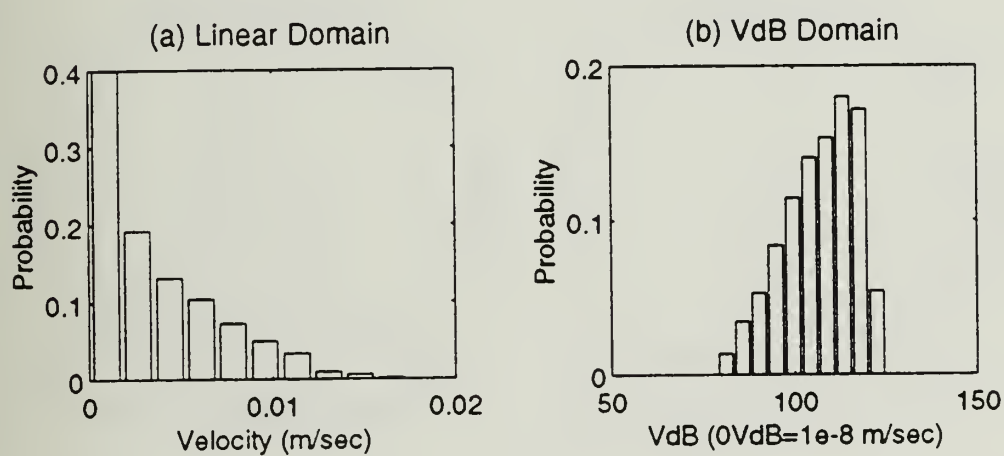
CG-59 Fire Pump

Pickup Location : PB(FE/A)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 3.105e+005

The sampling frequency : 1e+004 Hz



μ=0.003699	μ = 106.9
σ=0.003307	σ = 9.904
Skewness=1.086	*Skewness=-0.5187*
Kurtosis=3.515	*Kurtosis=2.472*

Figure D.5 The Statistical Analysis Results for Type I Fire Pumps Measured at PB(FE/A) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

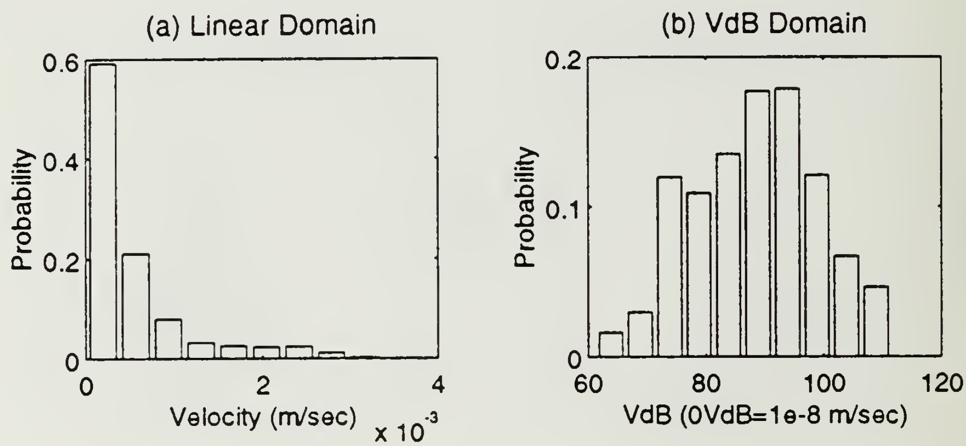
DDG Fire Pump

Pickup Location : MB(FE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 4.733e+004

The sampling frequency : 1e+004 Hz



μ=0.0005043	*μ = 88.39*
σ=0.0006038	*σ = 10.5*
Skewness=2.059	*Skewness=-0.1393*
Kurtosis=6.976	*Kurtosis=2.42*

Figure D.6 The Statistical Analysis Results for Type II Fire Pumps Measured at MB(FE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

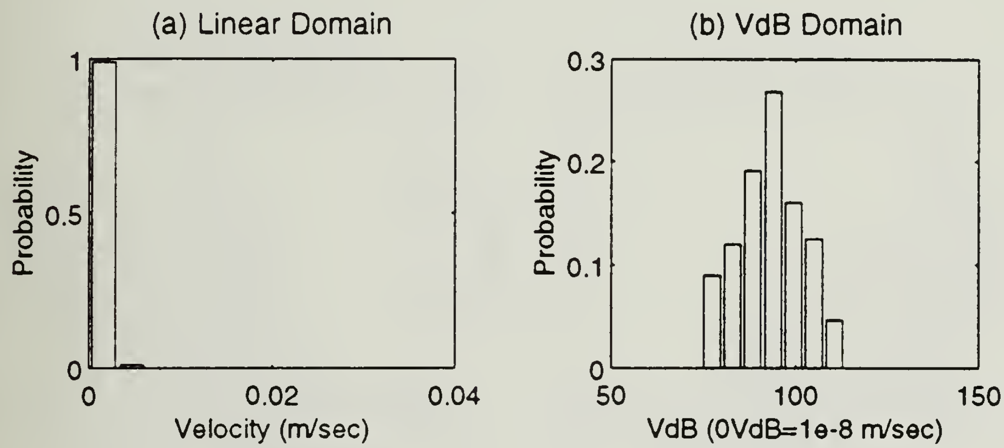
DDG Fire Pump

Pickup Location : MB(CE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 4.835e+004

The sampling frequency : 1e+004 Hz



μ=0.0007274	μ = 93.05
σ=0.0007633	σ = 8.784
Skewness=3.243	*Skewness=-0.0222*
Kurtosis=66.02	*Kurtosis=2.32*

Figure D.7 The Statistical Analysis Results for Type II Fire Pumps Measured at MB(CE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

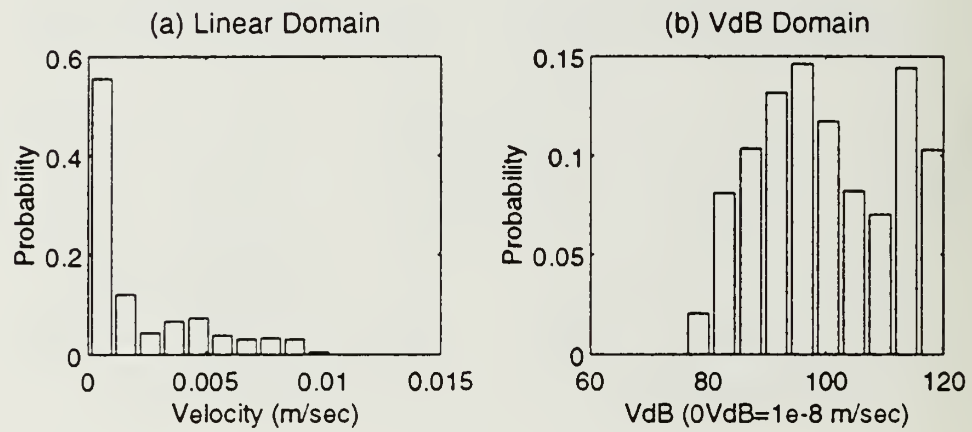
DDG Fire Pump

Pickup Location : MB(CE/A)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 3.089e+004

The sampling frequency : 1e+004 Hz



μ=0.002148	μ = 99.98
σ=0.002493	σ = 11.49
Skewness=1.321	*Skewness=0.01939*
Kurtosis=3.604	*Kurtosis=1.926*

Figure D.8 The Statistical Analysis Results for Type II Fire Pumps Measured at MB(CE/A) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

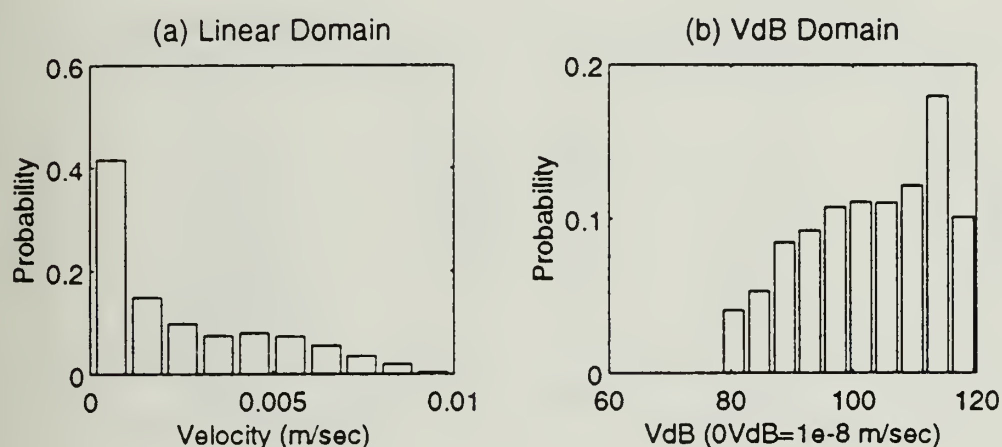
DDG Fire Pump

Pickup Location : PB(CE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 3.241e+004

The sampling frequency : 1e+004 Hz



μ=0.002484	μ = 102.6
σ=0.002344	σ = 10.84
Skewness=0.9047	*Skewness=-0.3675*
Kurtosis=2.675	*Kurtosis=2.038*

Figure D.9 The Statistical Analysis Results for Type II Fire Pumps Measured at PB(CE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

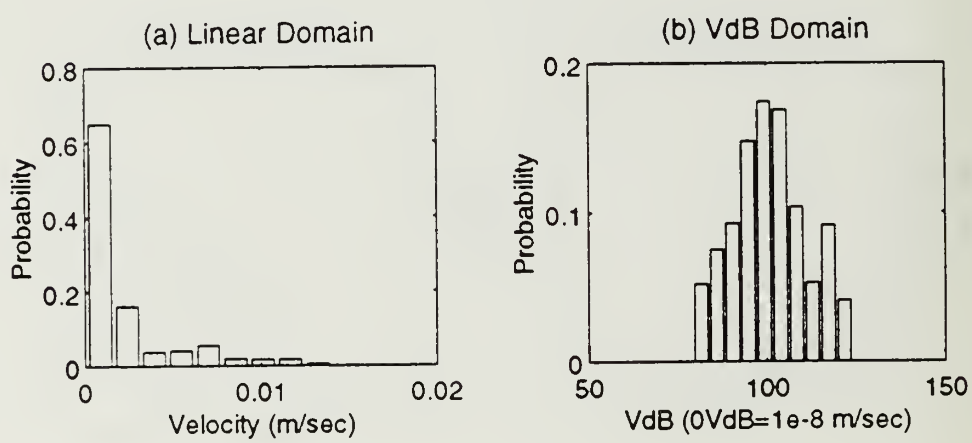
DDG Fire Pump

Pickup Location : PB(FE)

Data analysis by using : Cross peak with 1% threshold

Number of data points : 4.056e+004

The sampling frequency : 1e+004 Hz



(a)	(b)
μ=0.002166	*μ = 100.8*
σ=0.002739	*σ = 10.29*
Skewness=2.008	*Skewness=0.1128*
Kurtosis=6.446	*Kurtosis=2.366*

Figure D.10 The Statistical Analysis Results for Type II Fire Pumps Measured at PB(FE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

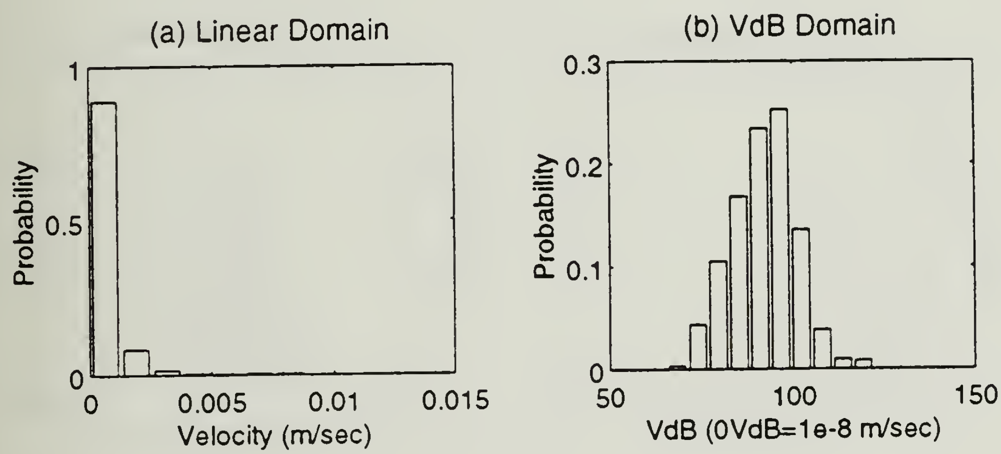
FF-1062 & FF-1071

Pickup Location : UMB

Data analysis by using : Cross peak with 1% threshold

Number of data points : 2.1e+005

The sampling frequency : 1e+004 Hz



μ=0.0006716	μ = 92.12
σ=0.0009258	σ = 8.687
Skewness=4.985	*Skewness=0.02892*
Kurtosis=36.52	*Kurtosis=2.953*

Figure D.11 The Statistical Analysis Results for Type III Fire Pumps Measured at UMB (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

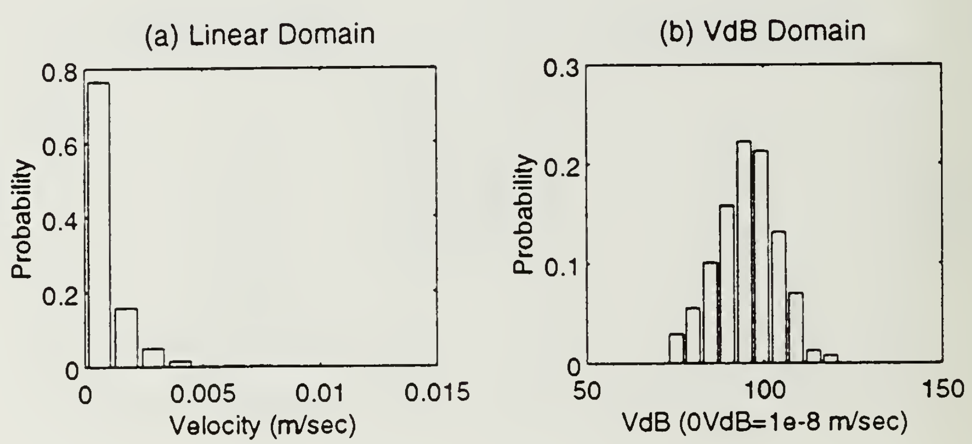
FF-1062 & FF-1071

Pickup Location : LMB

Data analysis by using : Cross peak with 1% threshold

Number of data points : 2.176e+005

The sampling frequency : 1e+004 Hz



(a)	(b)
μ=0.0009233	μ = 95.26
σ=0.001046	σ = 8.557
Skewness=3.35	*Skewness=-0.07739*
Kurtosis=19.59	*Kurtosis=2.697*

Figure D.12 The Statistical Analysis Results for Type III Fire Pumps Measured at LMB (a) Linear Velocity Domain (b) VdB Domain

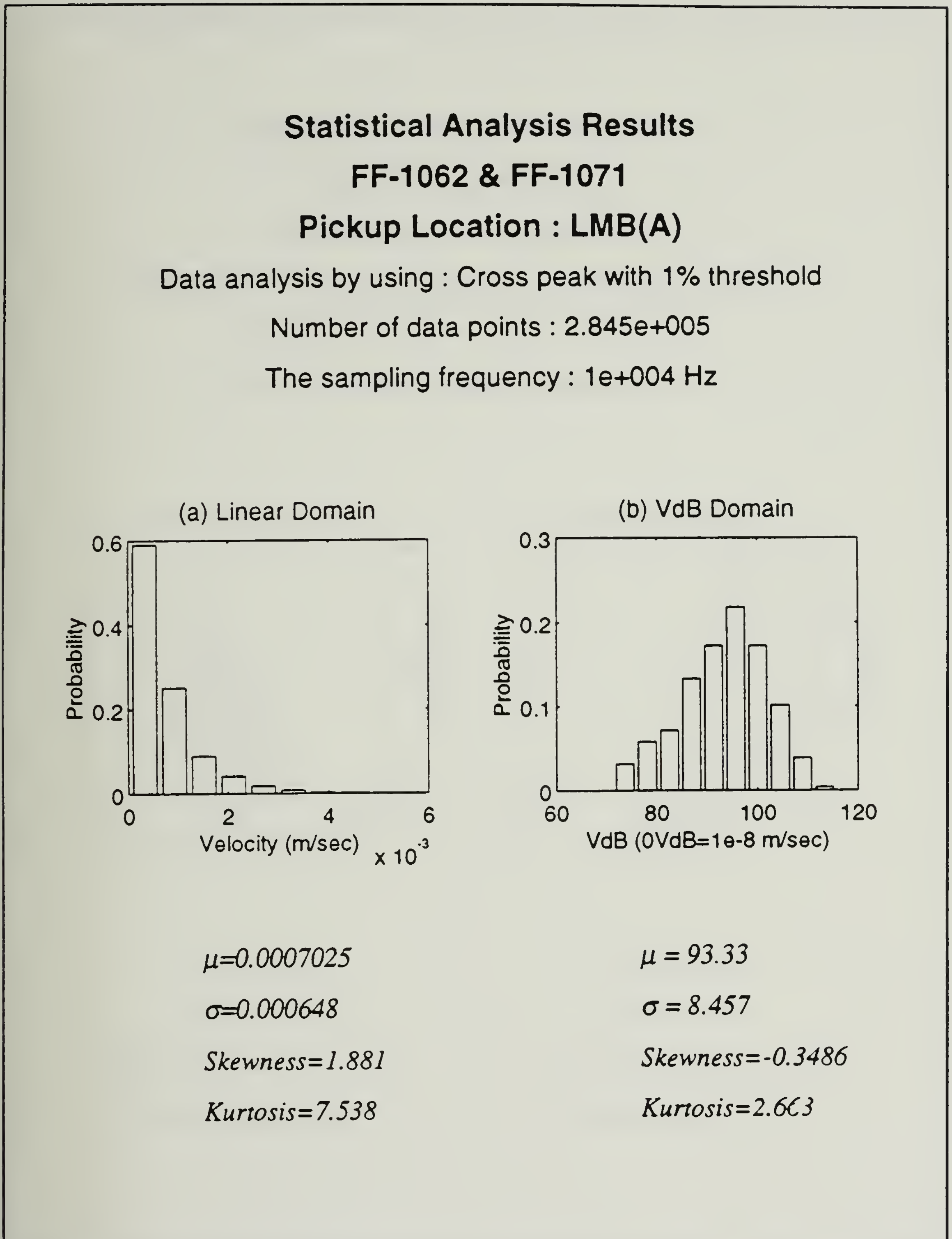


Figure D.13 The Statistical Analysis Results for Type III Fire Pumps Measured at LMB(A) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

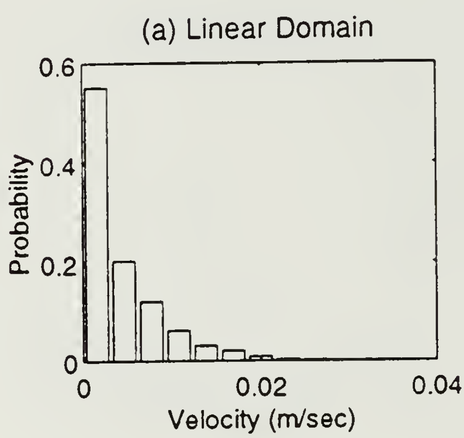
FF-1062 & FF-1071

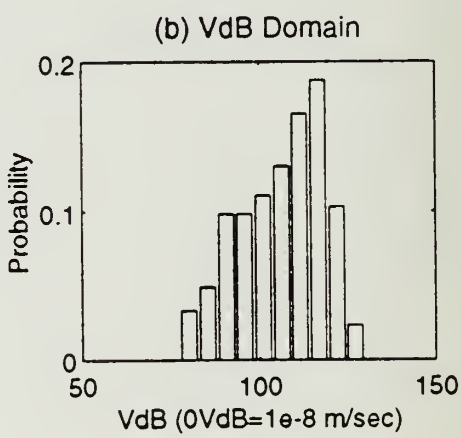
Pickup Location : UPB

Data analysis by using : Cross peak with 1% threshold

Number of data points : 1.367e+005

The sampling frequency : 1e+004 Hz





μ=0.004141

σ=0.004442

Skewness=1.57

Kurtosis=5.446

μ = 106.1

σ = 11.84

Skewness=-0.4083

Kurtosis=2.207

Figure D.14 The Statistical Analysis Results for Type III Fire Pumps Measured at UPB (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

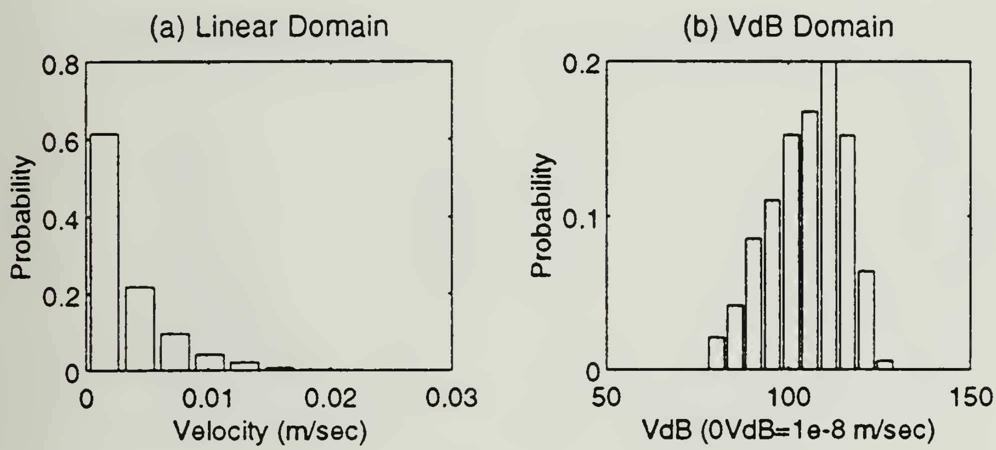
FF-1062 & FF-1071

Pickup Location : LPB

Data analysis by using : Cross peak with 1% threshold

Number of data points : 1.99e+005

The sampling frequency : 1e+004 Hz



(a) Linear Domain	(b) VdB Domain
μ=0.00316	μ = 105.1
σ=0.003246	σ = 10.2
Skewness=1.779	*Skewness=-0.3726*
Kurtosis=6.775	*Kurtosis=2.43*

Figure D.15 The Statistical Analysis Results for Type III Fire Pumps Measured at LPB (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

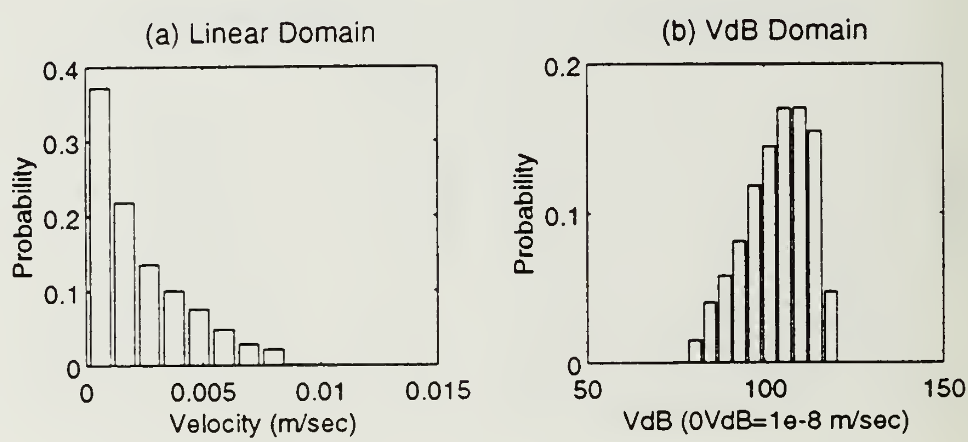
CG-59 Fire Pump

Pickup Location : PB(CE) w/o 89#6,90#3,90#6

Data analysis by using : Cross peak with 1% threshold

Number of data points : 2.704e+005

The sampling frequency : 1e+004 Hz



μ=0.002319	μ = 103.3
σ=0.001988	σ = 9.245
Skewness=1.046	*Skewness=-0.5101*
Kurtosis=3.304	*Kurtosis=2.506*

Figure D.16 The Statistical Analysis Results (Without Damaged) for Type I Fire Pumps Measured at PB(CE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

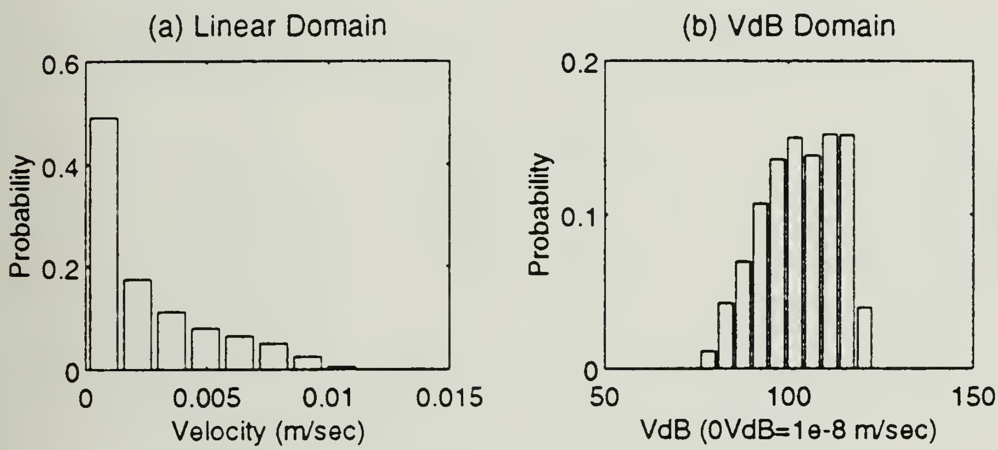
CG-59 Fire Pump

Pickup Location : PB(FE) w/o 90#3

Data analysis by using : Cross peak with 1% threshold

Number of data points : 2.489e+005

The sampling frequency : 1e+004 Hz



(a)	(b)
μ=0.002525	μ = 103
σ=0.002472	σ = 10.3
Skewness=1.169	*Skewness=-0.3165*
Kurtosis=3.409	*Kurtosis=2.228*

Figure D.17 The Statistical Analysis Results (Without Damaged) for Type I Fire Pumps Measured at PB(FE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

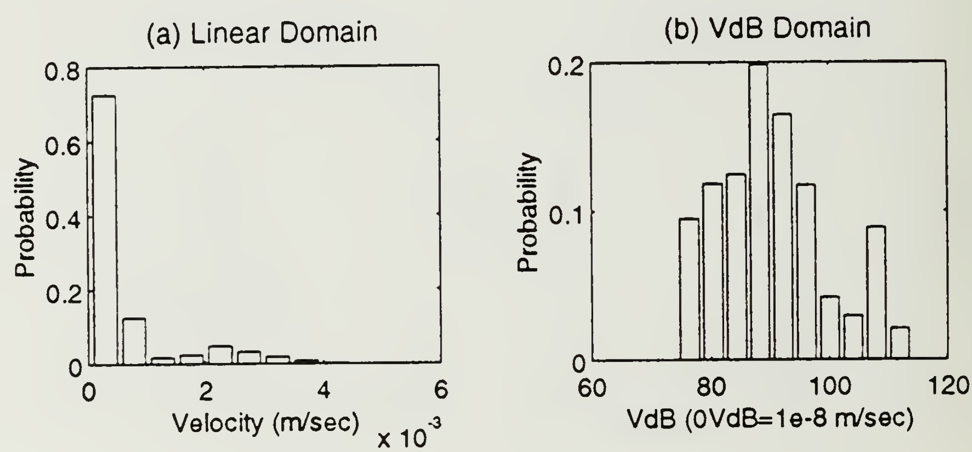
DDG-994 Fire Pump

Pickup Location : MB(CE) w/o #1

Data analysis by using : Cross peak with 1% threshold

Number of data points : 3.238e+004

The sampling frequency : 1e+004 Hz



μ=0.0006192	μ = 90.52
σ=0.0008105	σ = 9.194
Skewness=2.146	*Skewness=0.4951*
Kurtosis=6.762	*Kurtosis=2.566*

Figure D.18 The Statistical Analysis Results (Without Damaged) for Type II Fire Pumps Measured at MB(CE) (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

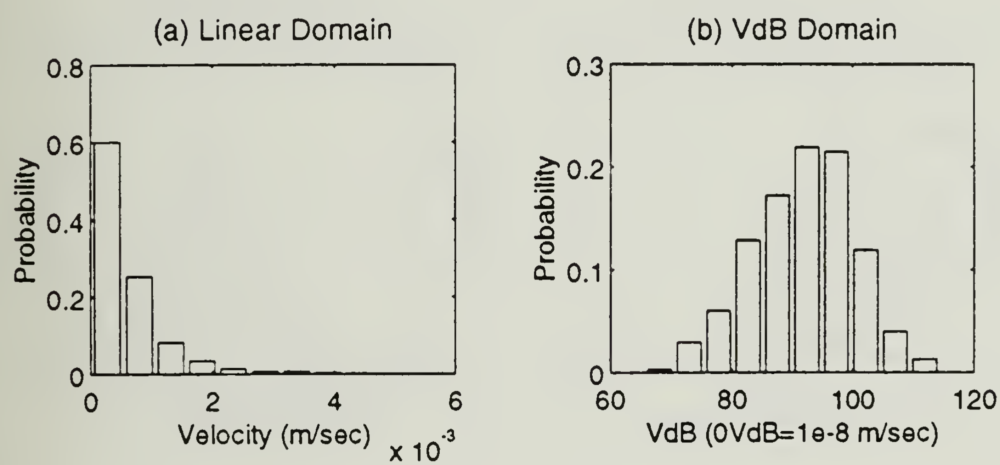
FF-1062 & FF-1071

Pickup Location : UMB w/o 62#1

Data analysis by using : Cross peak with 1% threshold

Number of data points : 2.05e+005

The sampling frequency : 1e+004 Hz



μ=0.0005973	μ = 91.81
σ=0.0006017	σ = 8.338
Skewness=2.488	*Skewness=-0.1669*
Kurtosis=11.46	*Kurtosis=2.595*

Figure D.19 The Statistical Analysis Results (Without Damaged) for Type III Fire Pumps Measured at UMB (a) Linear Velocity Domain (b) VdB Domain

Statistical Analysis Results

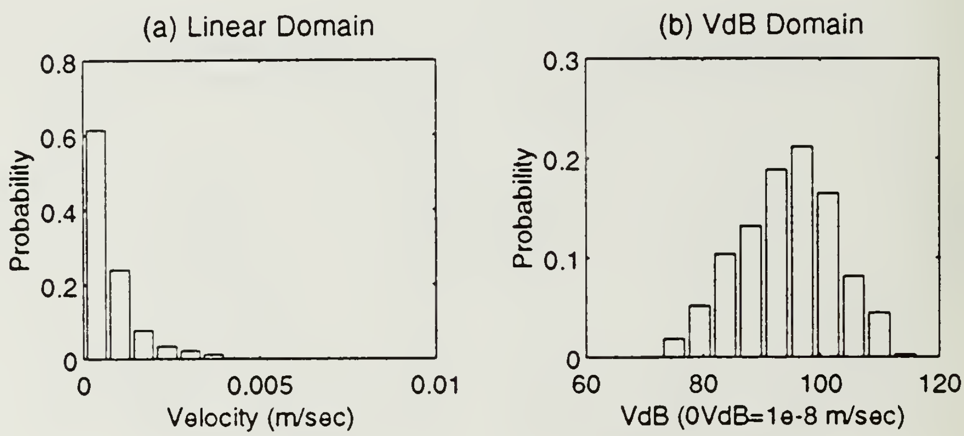
FF-1062 & FF-1071

Pickup Location : LMB w/o 62#1,71#2

Data analysis by using : Cross peak with 1% threshold

Number of data points : 1.873e+005

The sampling frequency : 1e+004 Hz



(a) Linear Domain	(b) VdB Domain
μ=0.0007757	μ = 94.27
σ=0.0007364	σ = 8.15
Skewness=1.98	Skewness=-0.181
Kurtosis=7.43	Kurtosis=2.555

Figure D.20 The Statistical Analysis Results (Without Damaged) for Type III Fire Pumps Measured at LMB (a) Linear Velocity Domain (b) VdB Domain

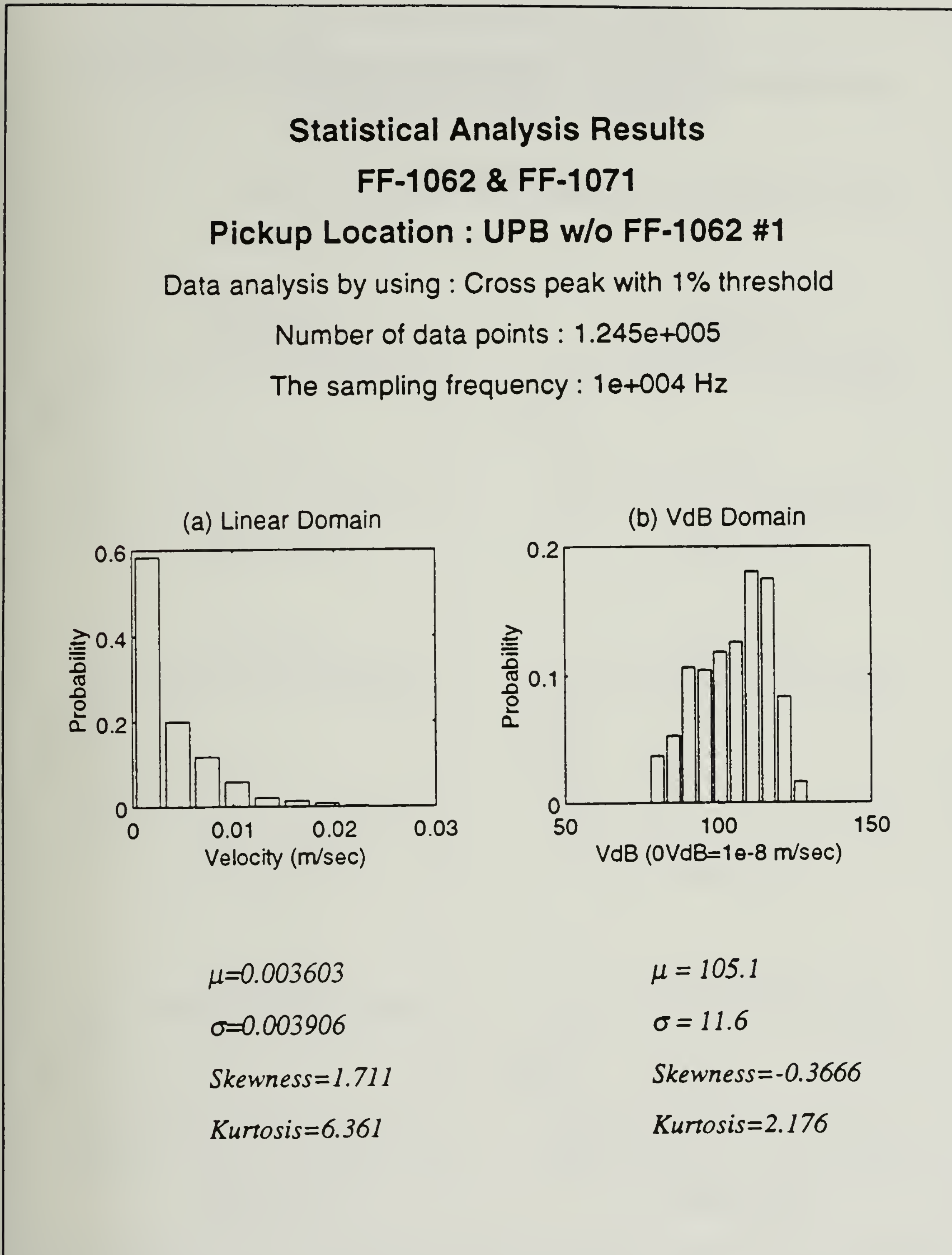


Figure D.21 The Statistical Analysis Results (Without Damaged) for Type III Fire Pumps Measured at UPB (a) Linear Velocity Domain (b) VdB Domain

APPENDIX E. FIGURES OF 1/1 OCTAVE BAND LEVELS

This section contains all the figures of 1/1 octave band levels.

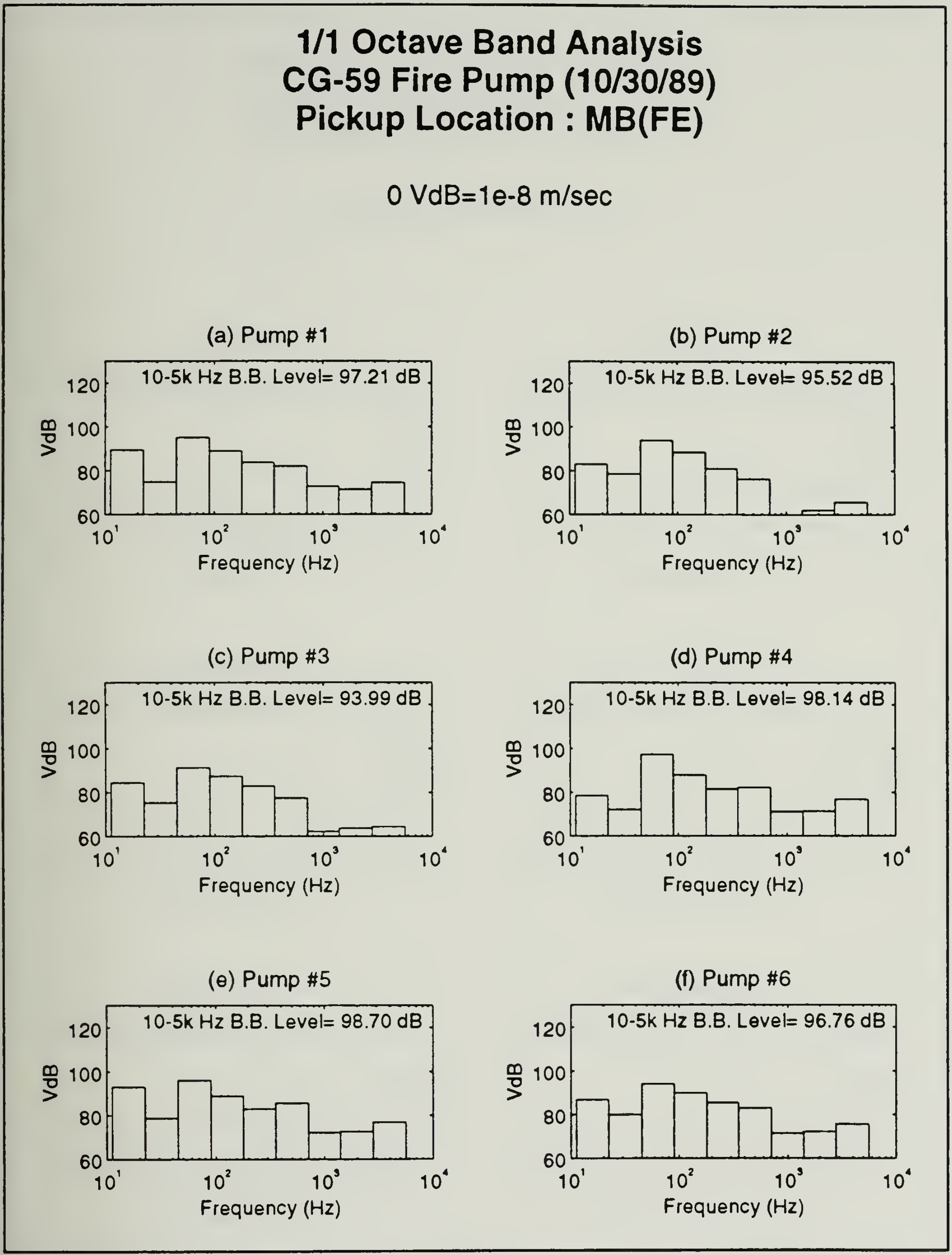


Figure E.1 The 1/1 Octave Band Analysis Results for CG-59(10/30/89) Fire Pumps Measured at MB(FE)

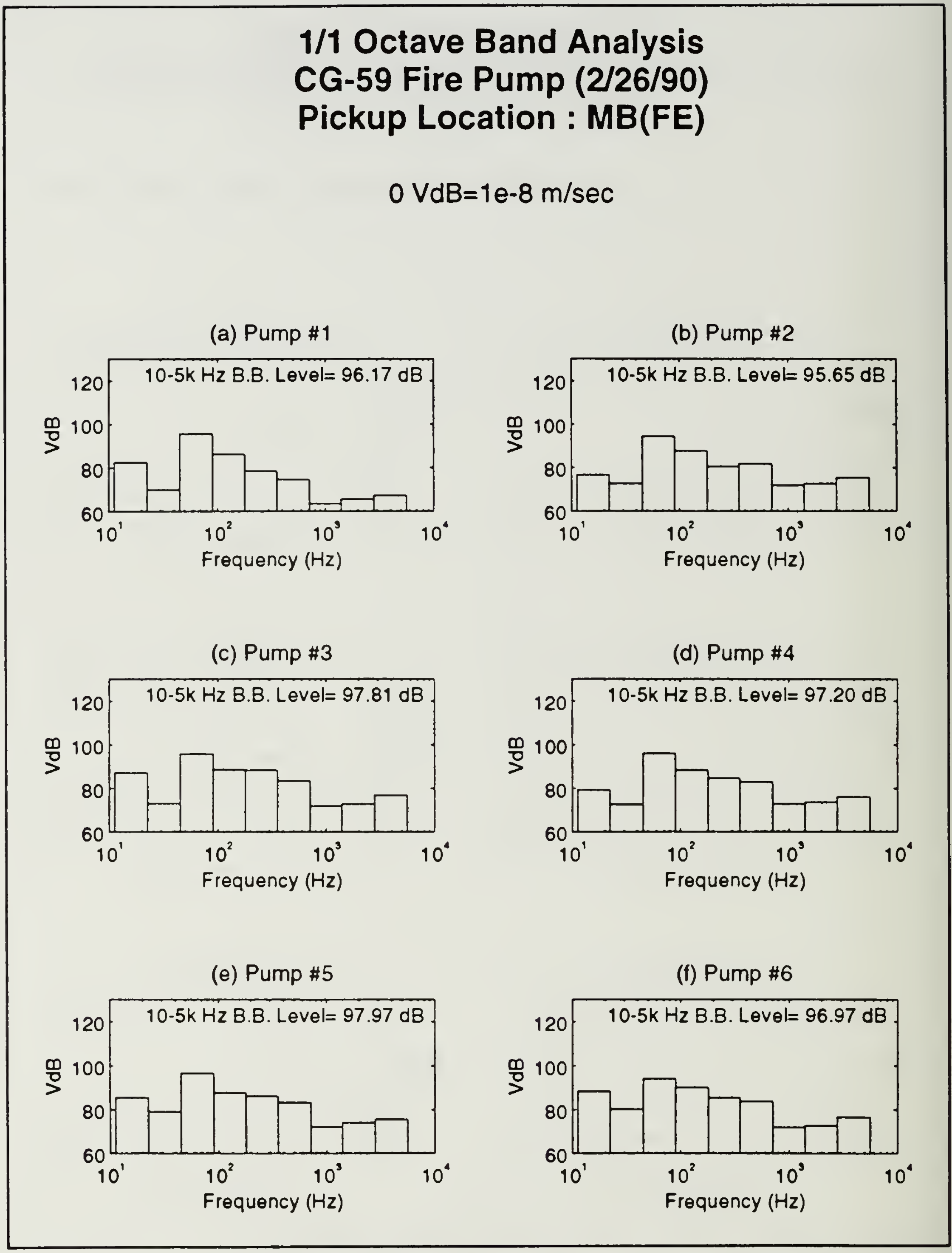


Figure E.2 The 1/1 Octave Band Analysis Results for CG-59(2/26/90) Fire Pumps Measured at MB(FE)

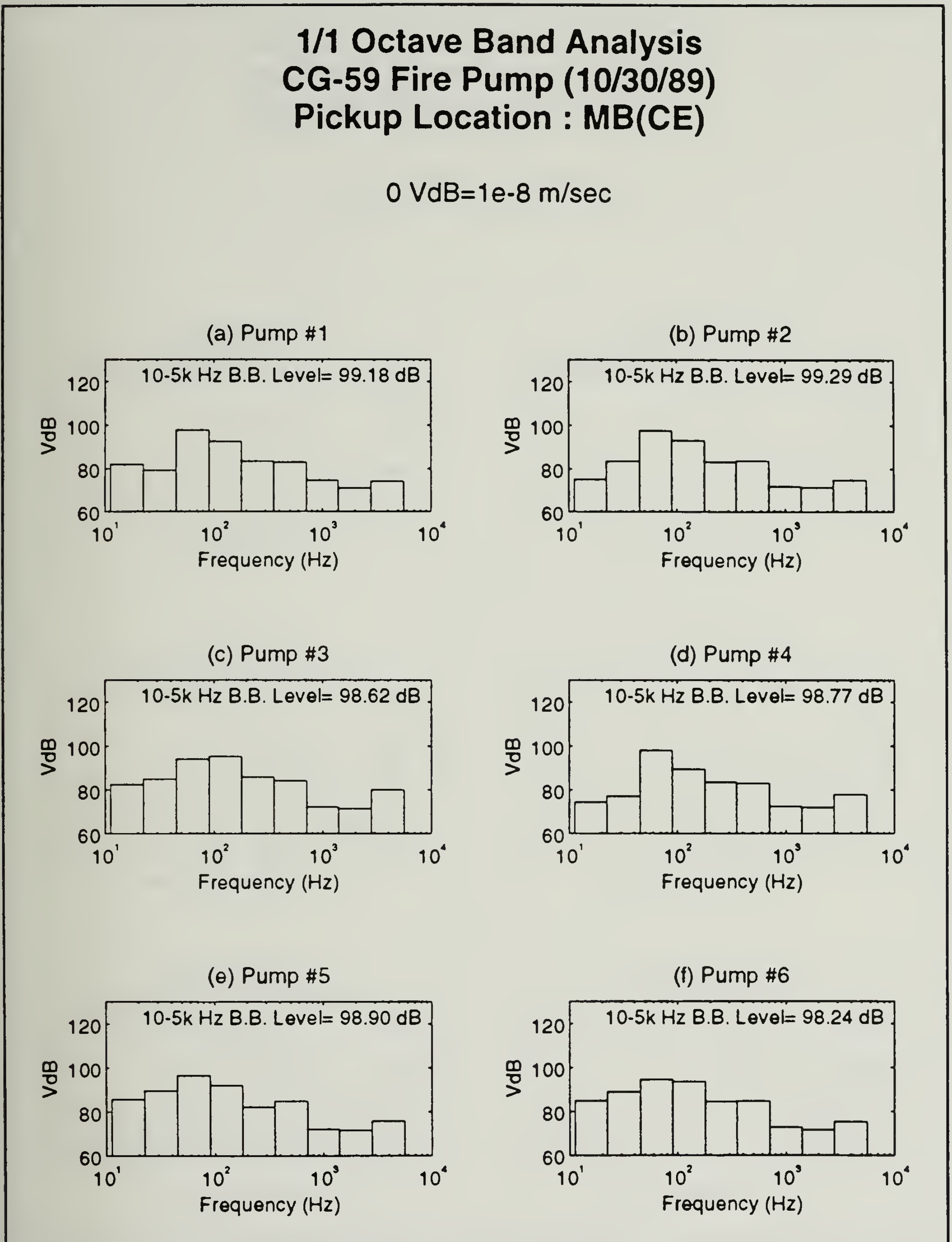


Figure E.3 The 1/1 Octave Band Analysis Results for CG-59(10/30/89) Fire Pumps Measured at MB(CE)

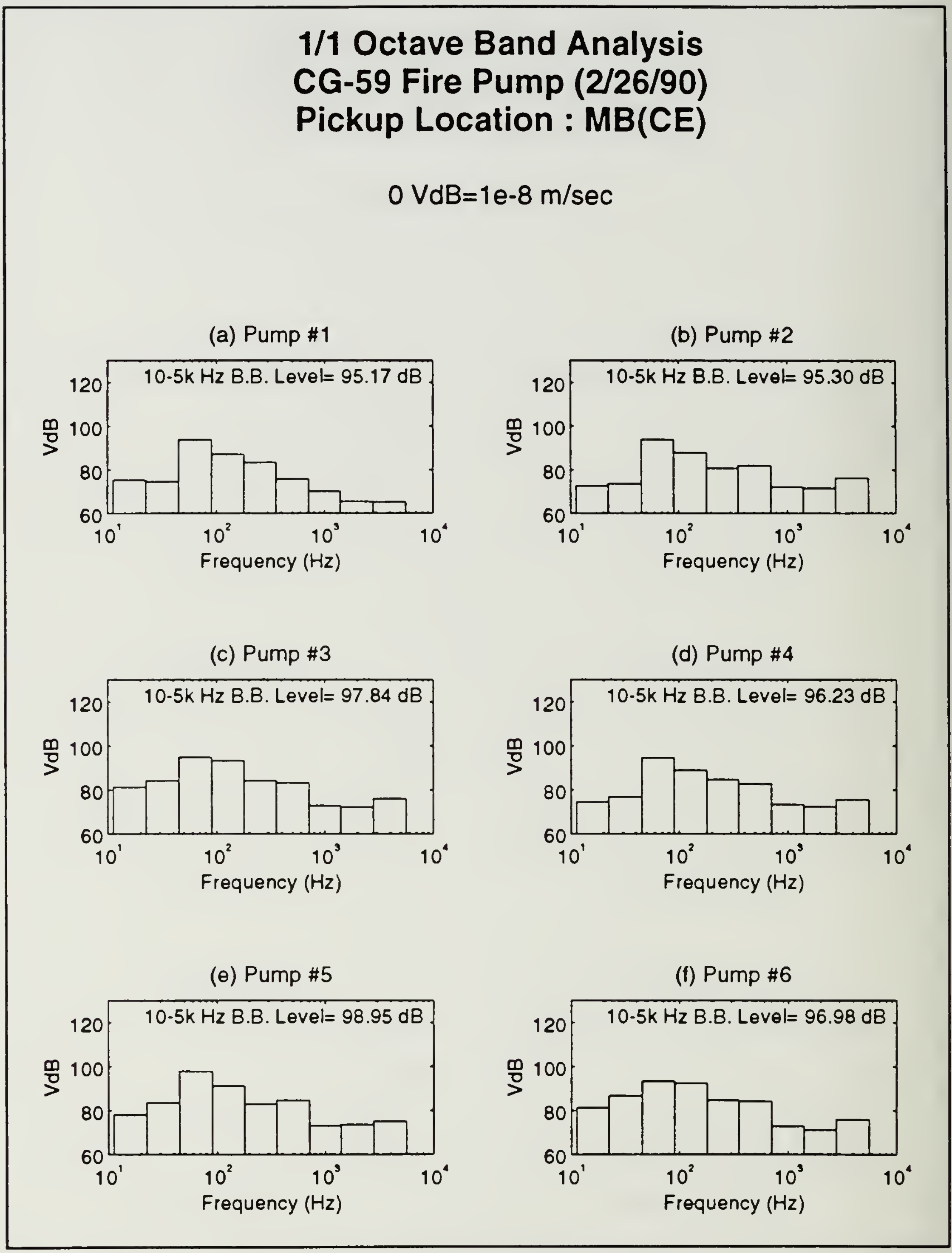


Figure E.4 The 1/1 Octave Band Analysis Results for CG-59(2/26/90) Fire Pumps Measured at MB(CE)

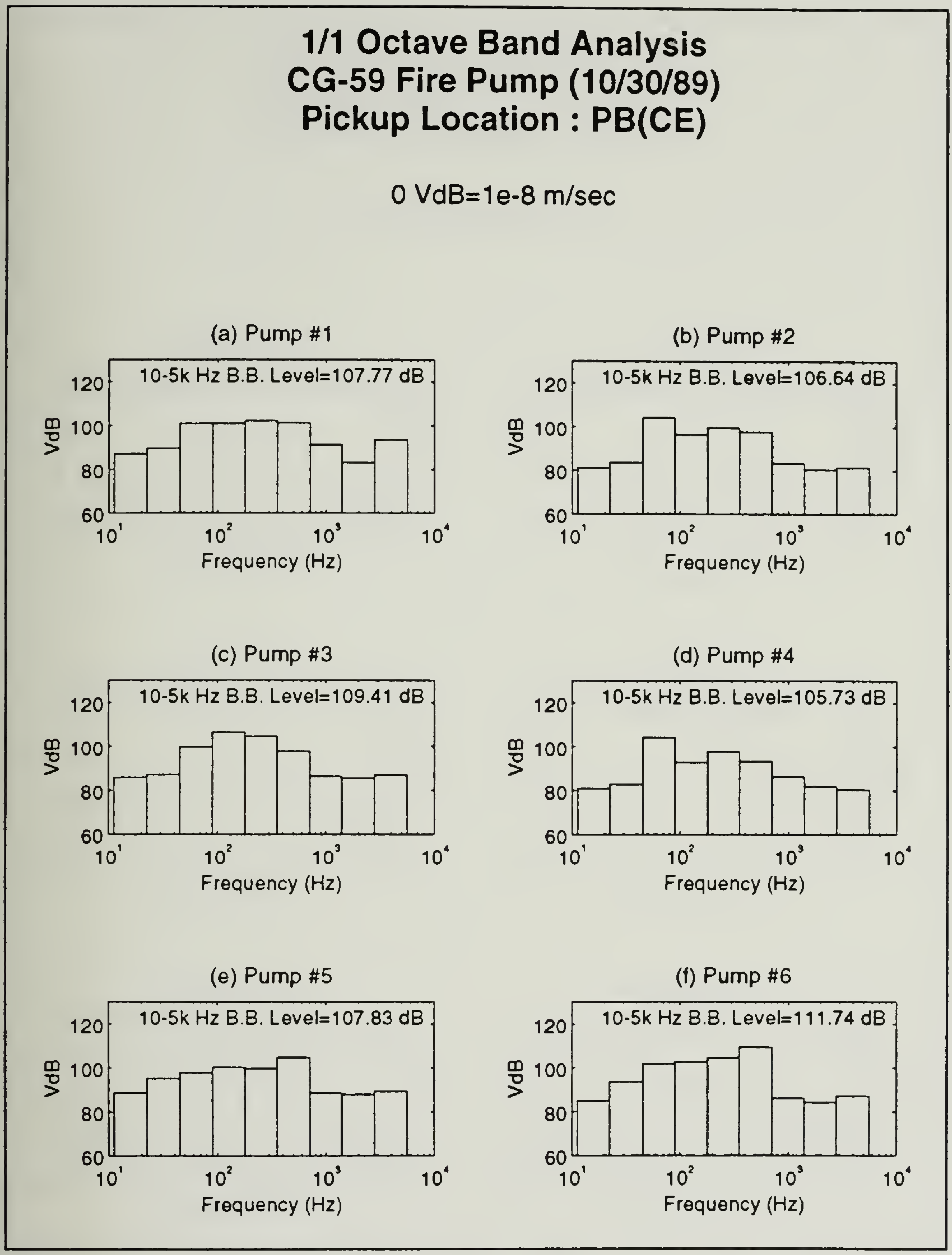


Figure E.5 The 1/1 Octave Band Analysis Results for CG-59(10/30/89) Fire Pumps Measured at PB(CE)

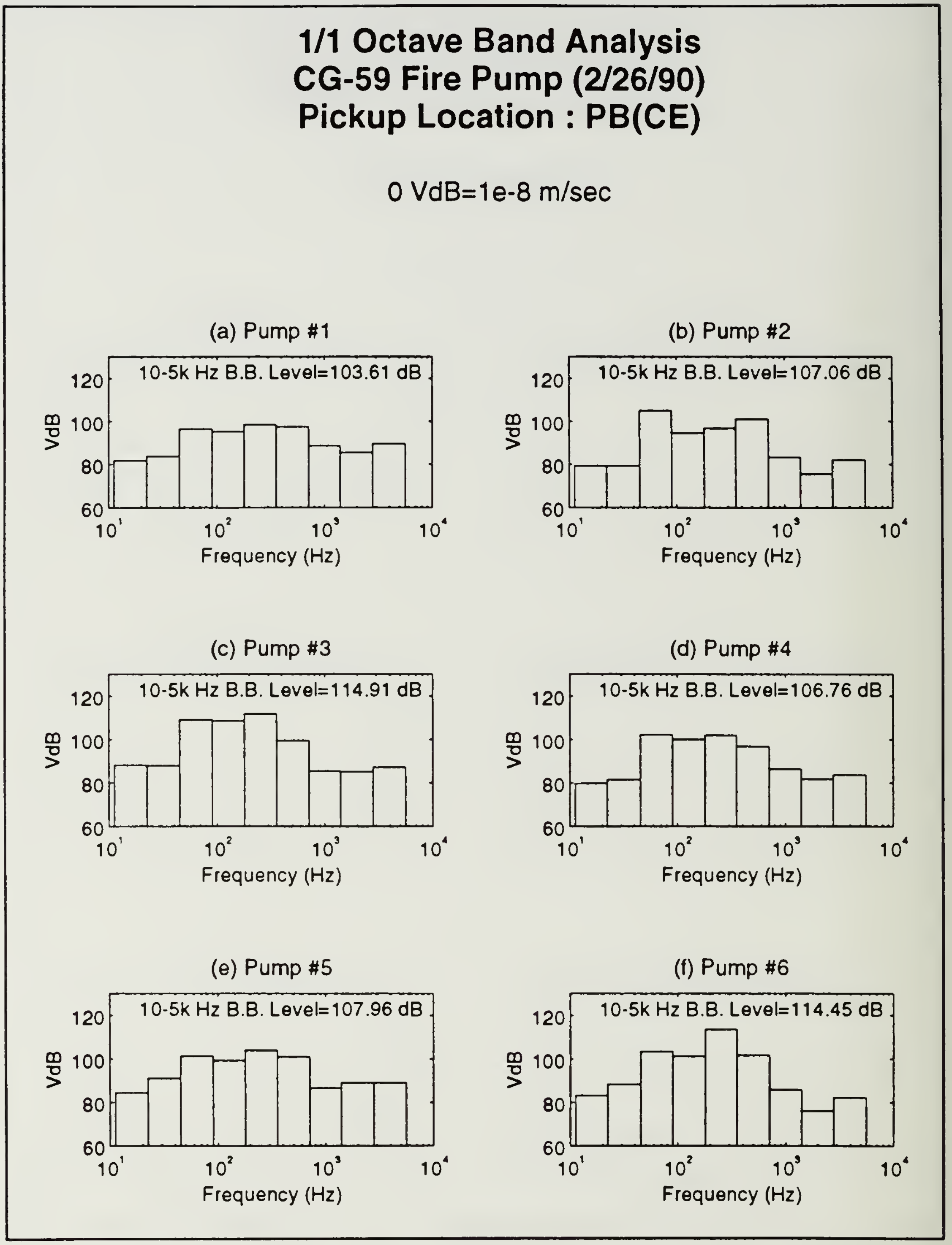


Figure E.6 The 1/1 Octave Band Analysis Results for CG-59(2/26/90) Fire Pumps Measured at PB(CE)

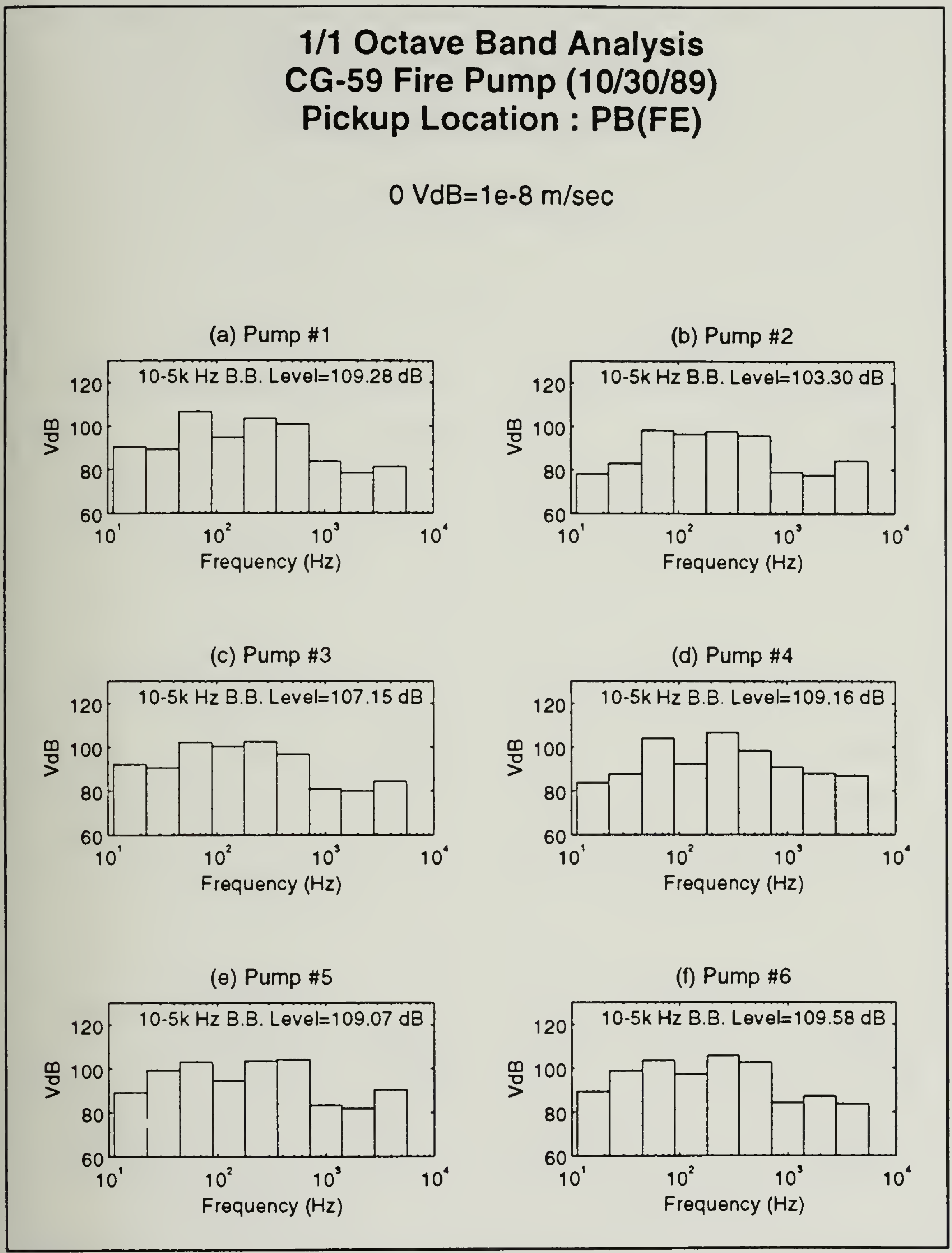


Figure E.7 The 1/1 Octave Band Analysis Results for CG-59(10/30/89) Fire Pumps Measured at PB(FE)

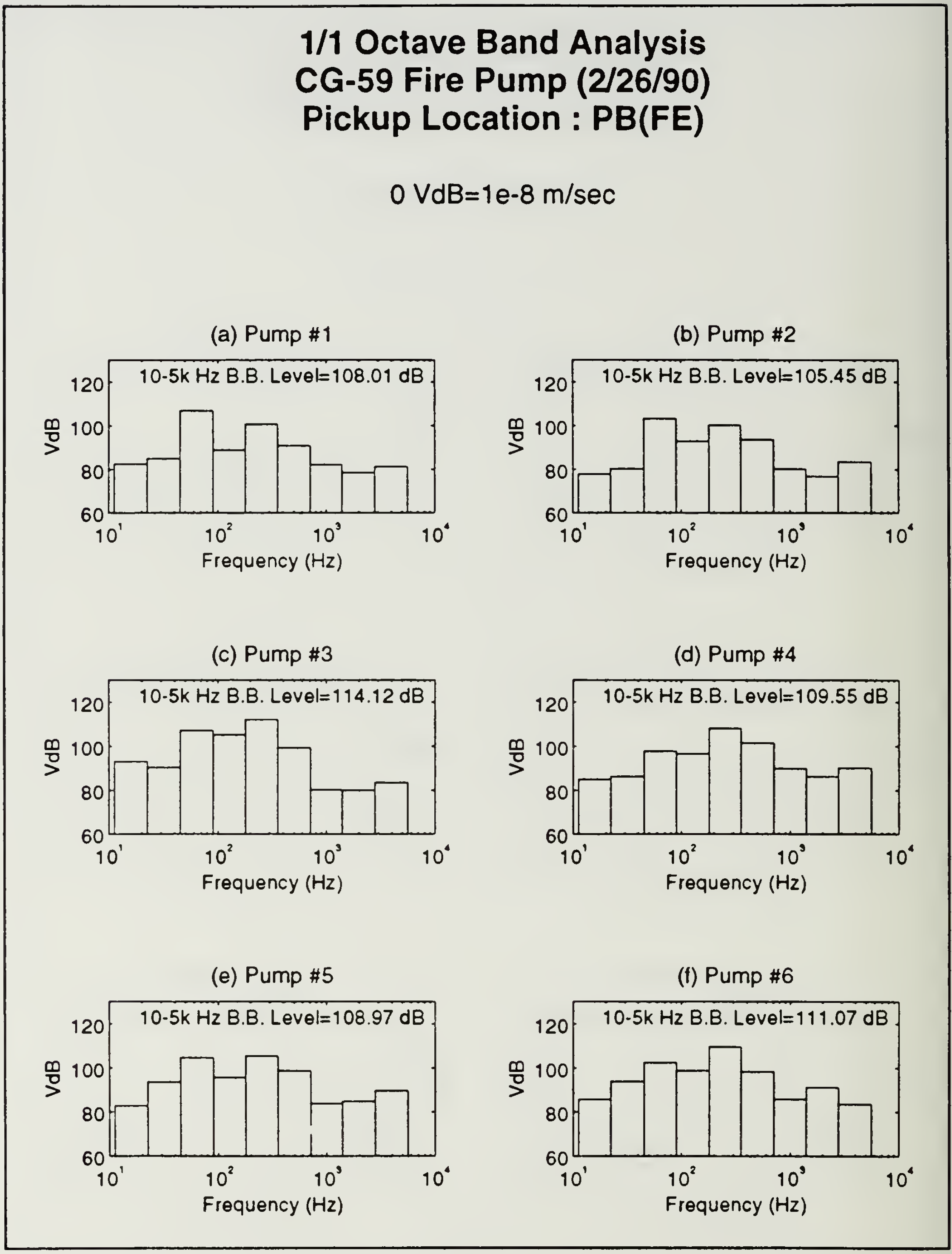


Figure E.8 The 1/1 Octave Band Analysis Results for CG-59(2/26/90) Fire Pumps Measured at PB(FE)

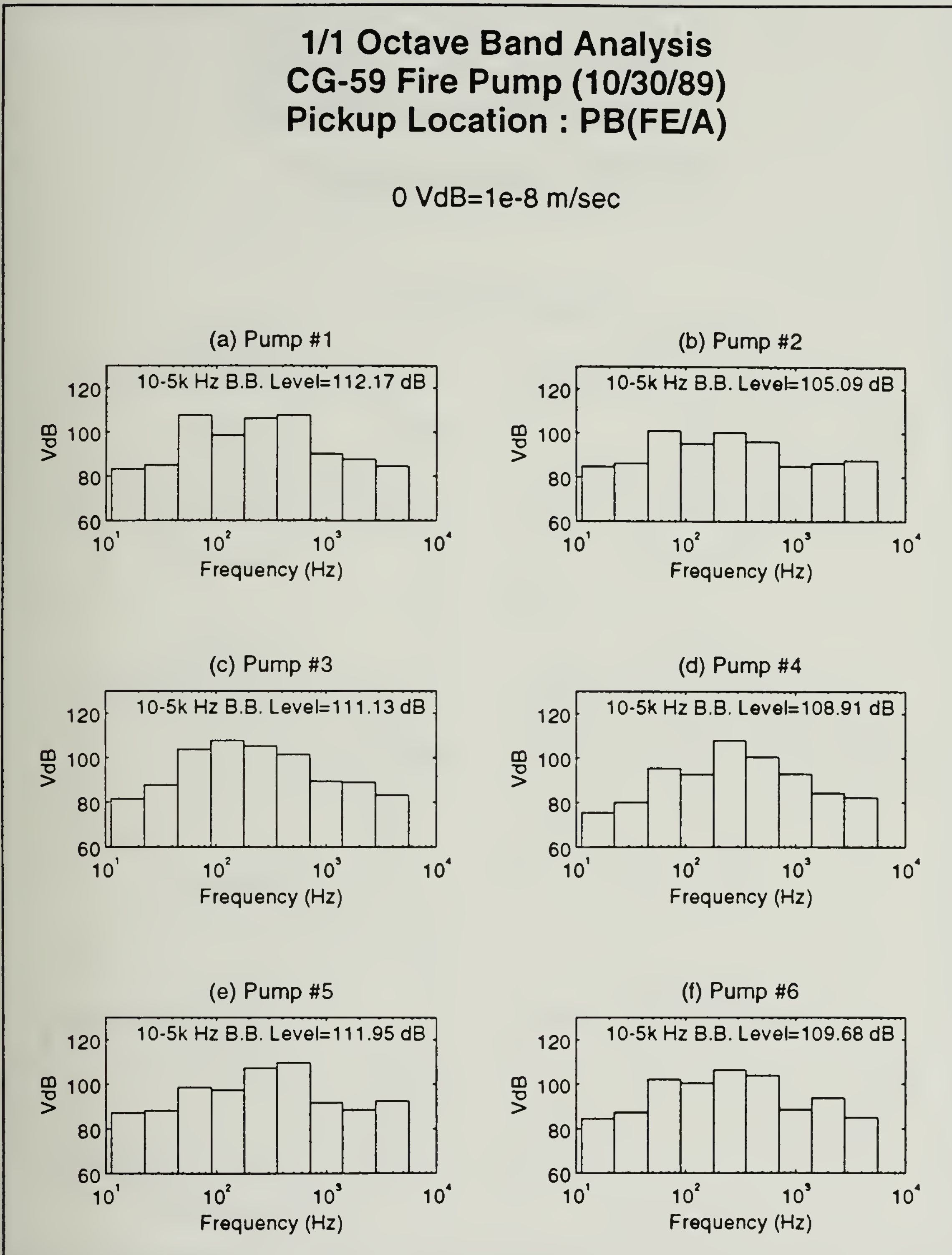


Figure E.9 The 1/1 Octave Band Analysis Results for CG-59(10/30/89) Fire Pumps Measured at PB(FE/A)

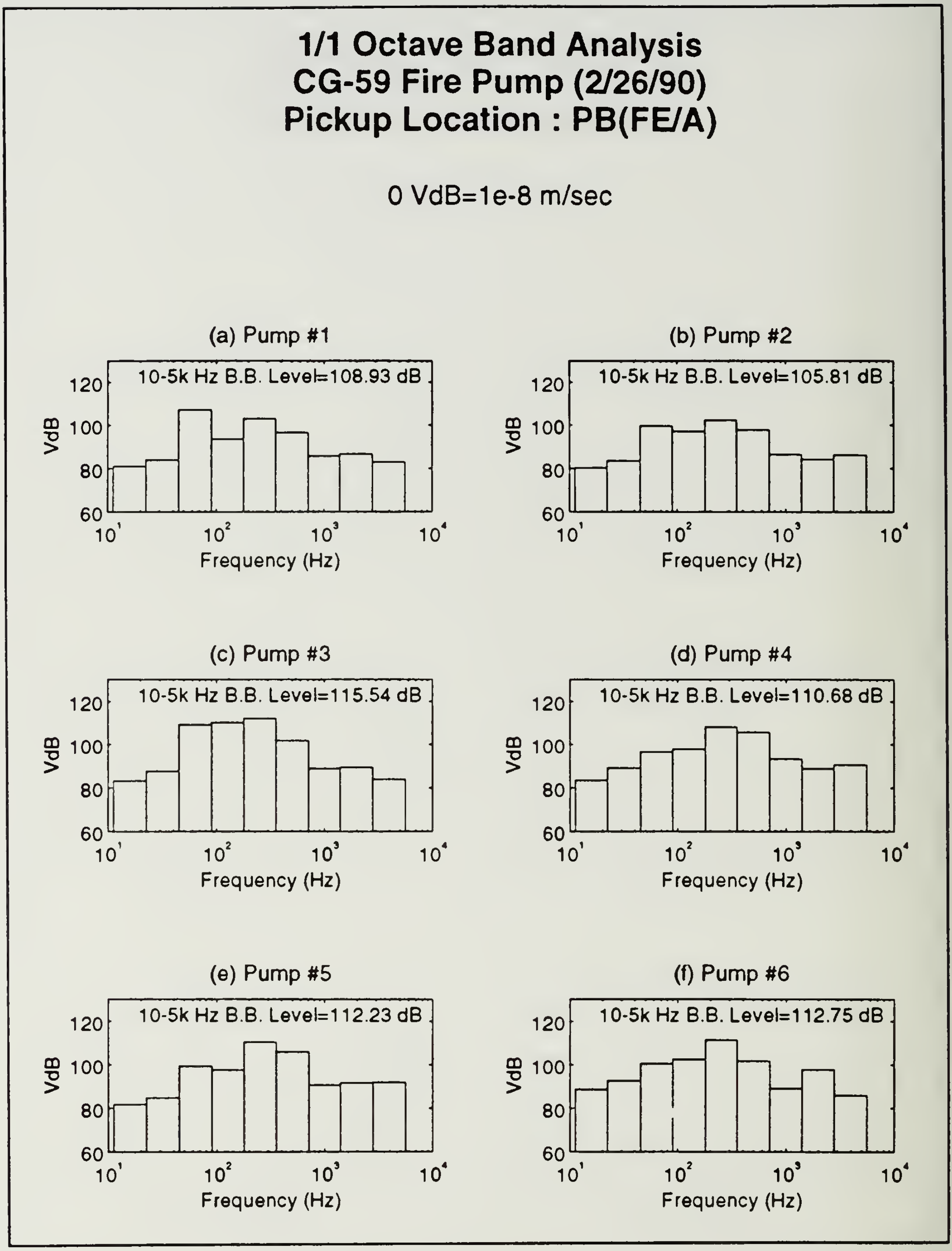


Figure E.10 The 1/1 Octave Band Analysis Results for CG-59(2/26/90) Fire Pumps Measured at PB(FE/A)

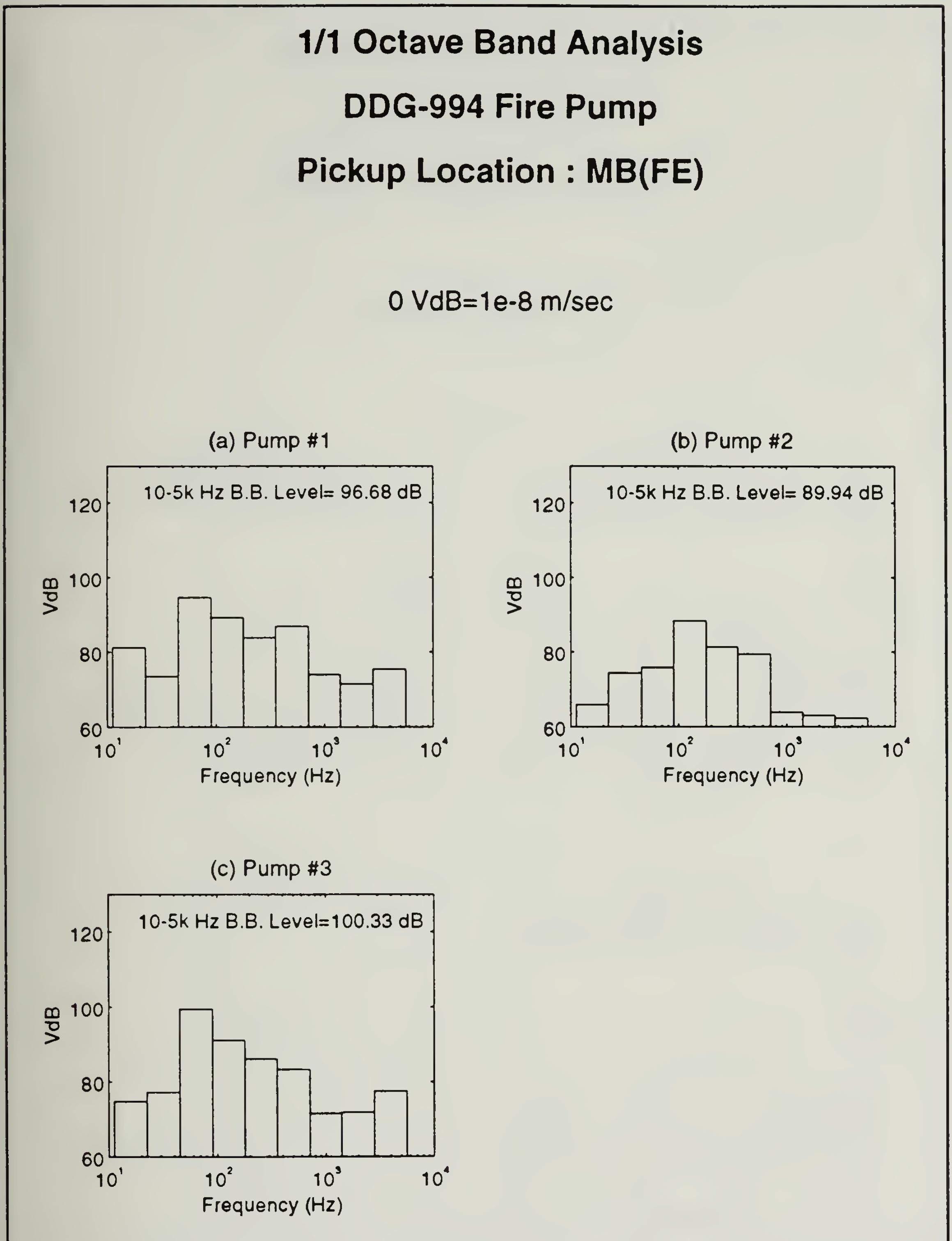


Figure E.11 The 1/1 Octave Band Analysis Results for DDG-994 Fire Pumps Measured at MB(FE)

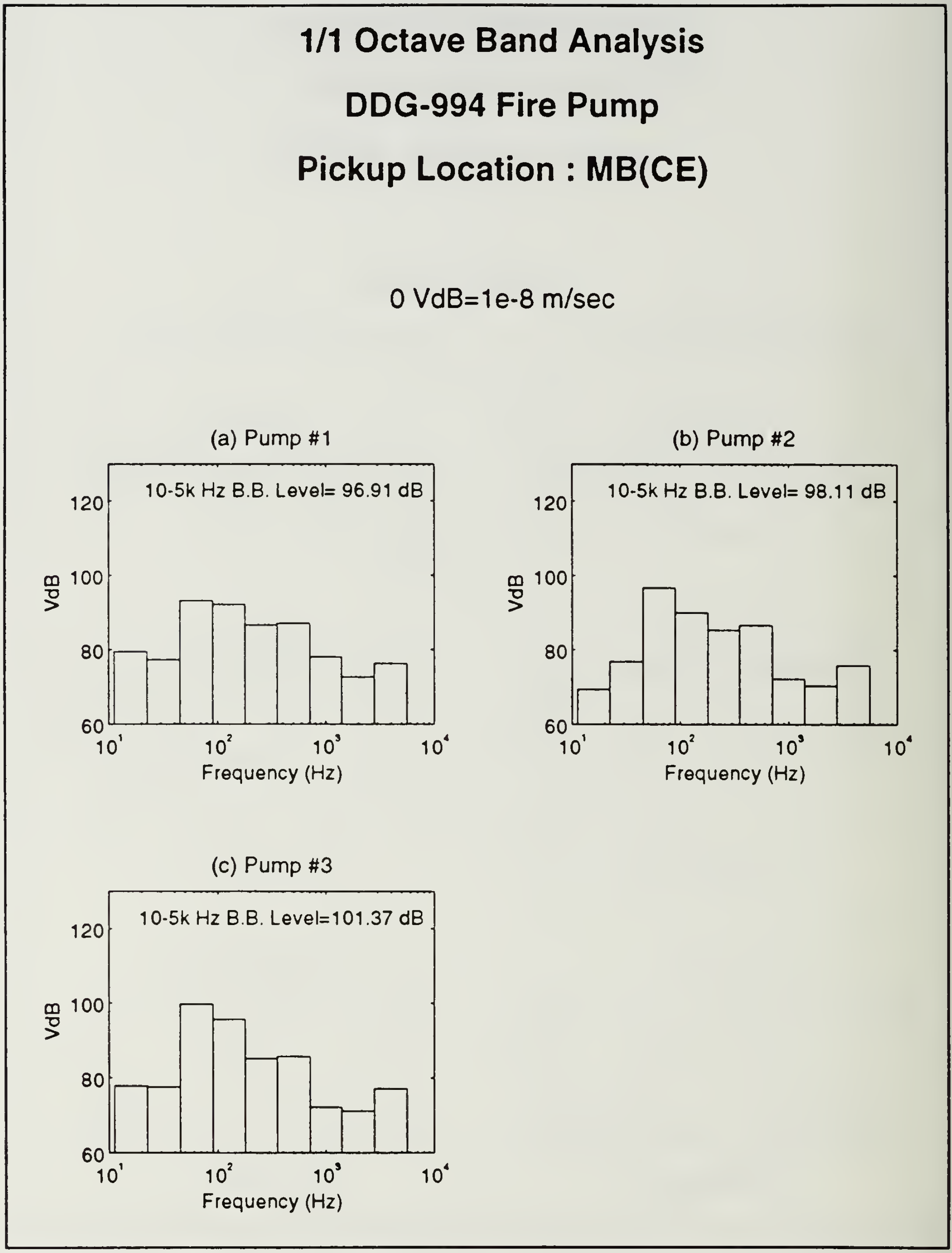


Figure E.12 The 1/1 Octave Band Analysis Results for DDG-994 Fire Pumps Measured at MB(CE)

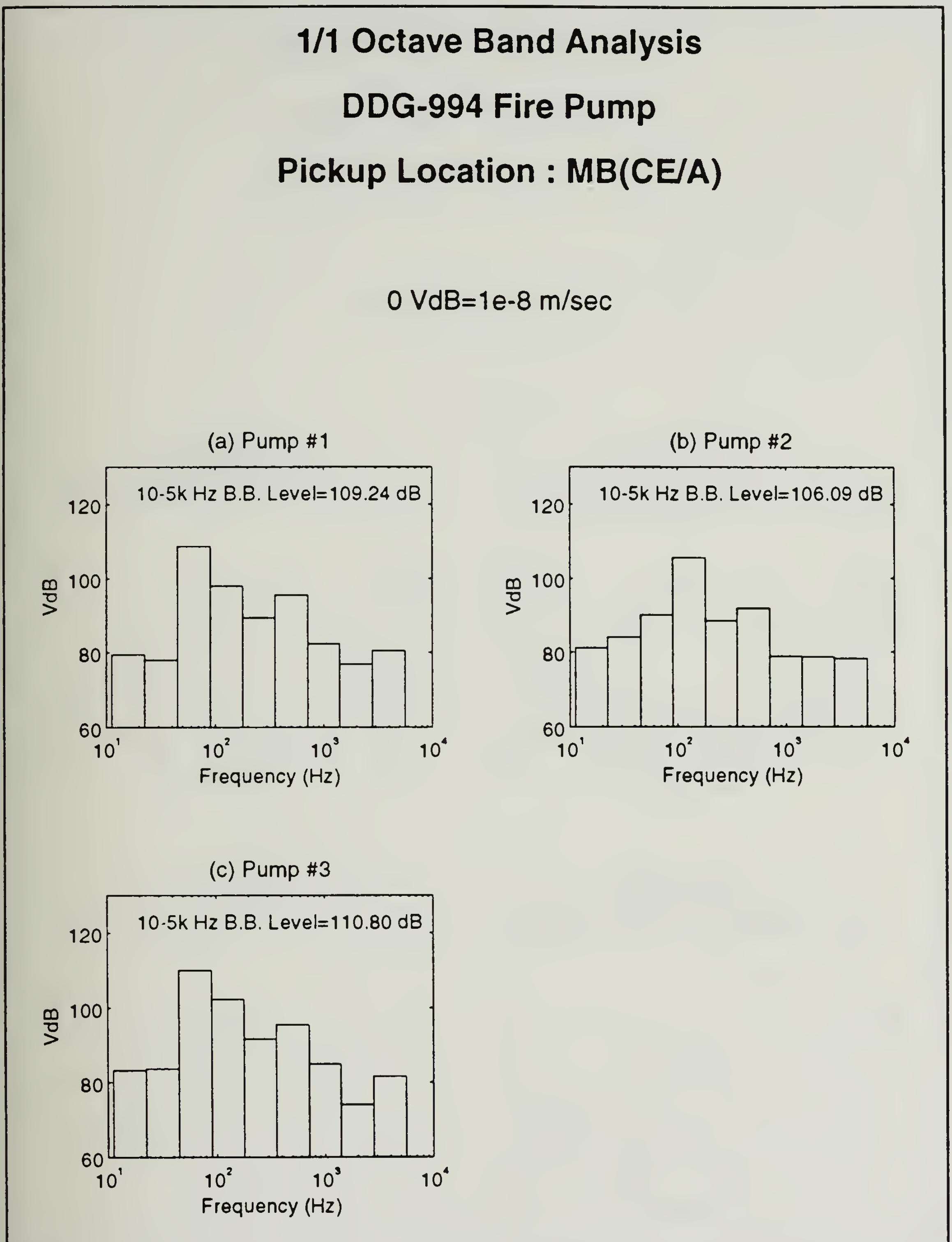


Figure E.13 The 1/1 Octave Band Analysis Results for DDG-994 Fire Pumps Measured at MB(CE/A)

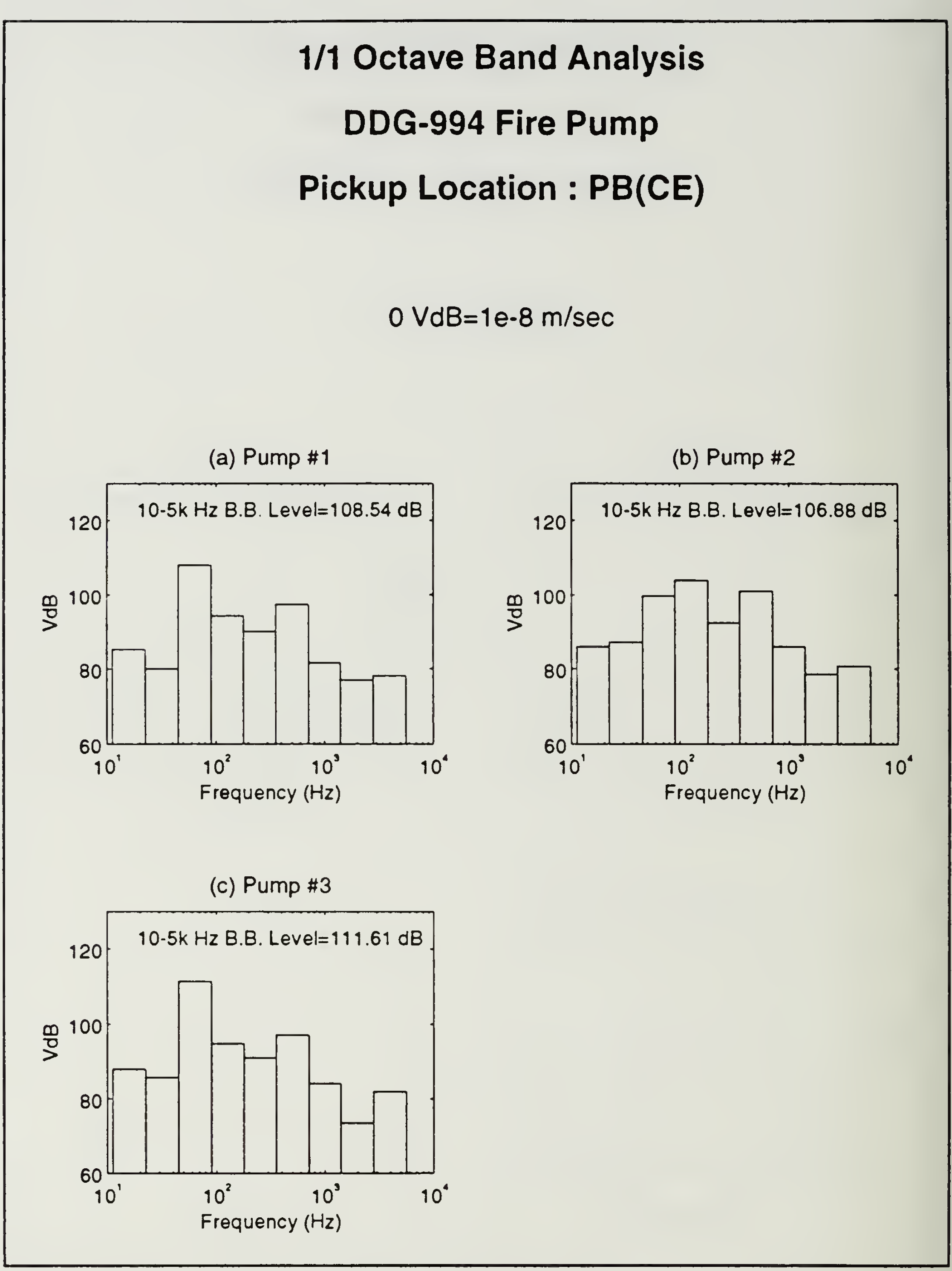


Figure E.14 The 1/1 Octave Band Analysis Results for DDG-994 Fire Pumps Measured at PB(CE)

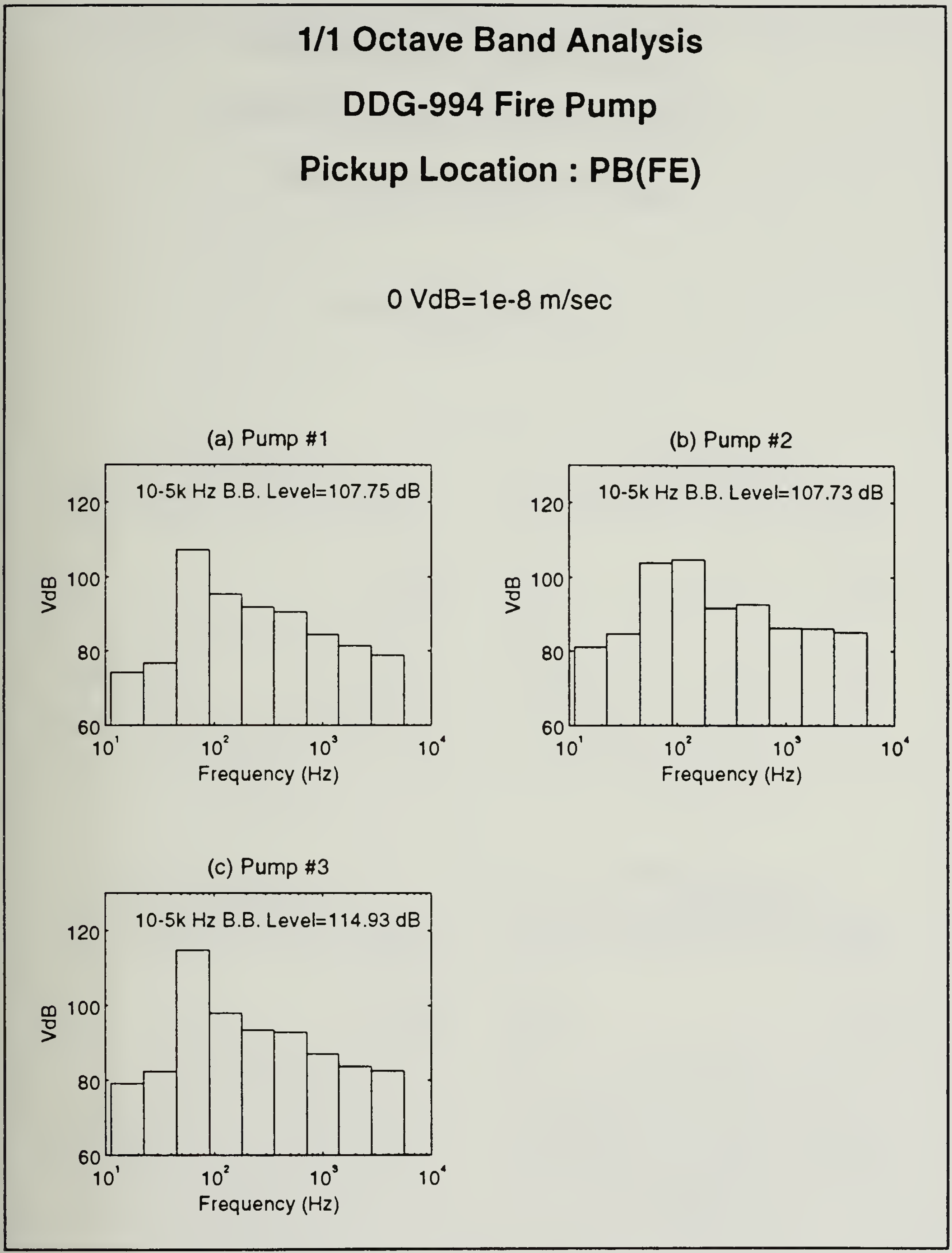


Figure E.15 The 1/1 Octave Band Analysis Results for DDG-994 Fire Pumps Measured at PB(FE)

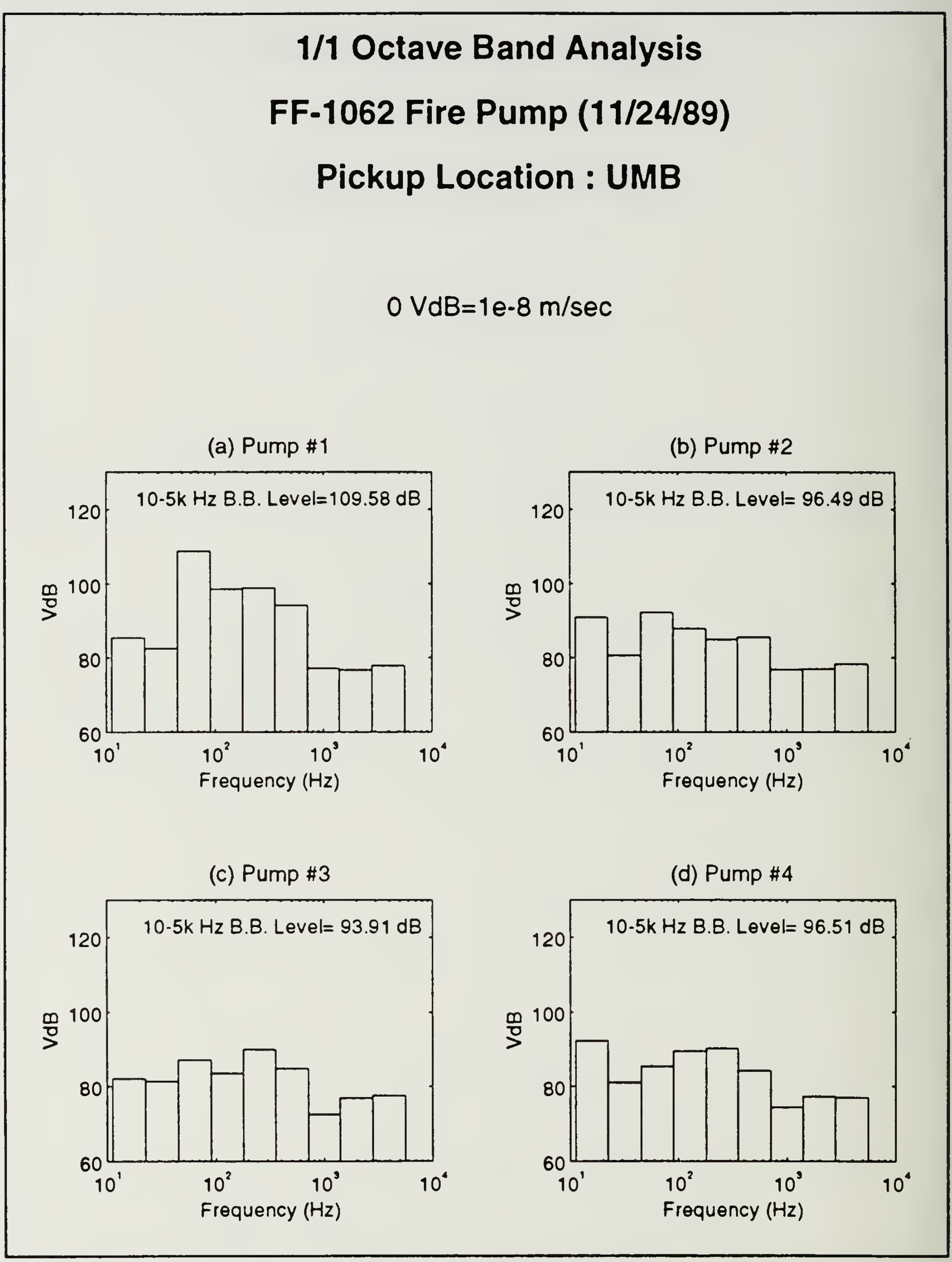


Figure E.16 The 1/1 Octave Band Analysis Results for FF-1062 (11/24/89) Fire Pumps Measured at UMB

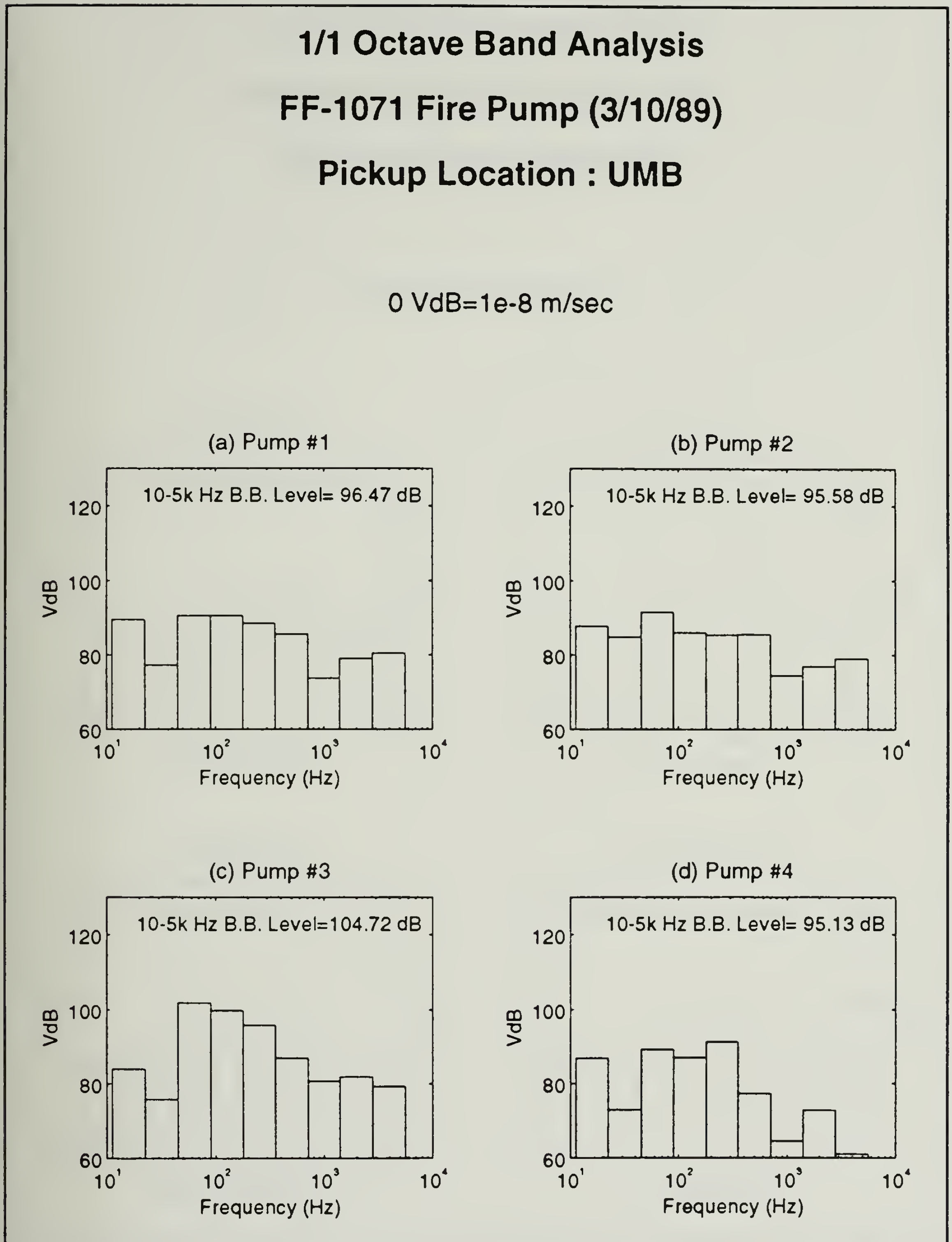


Figure E.17 The 1/1 Octave Band Analysis Results for FF-1071(3/10/89) Fire Pumps Measured at UMB

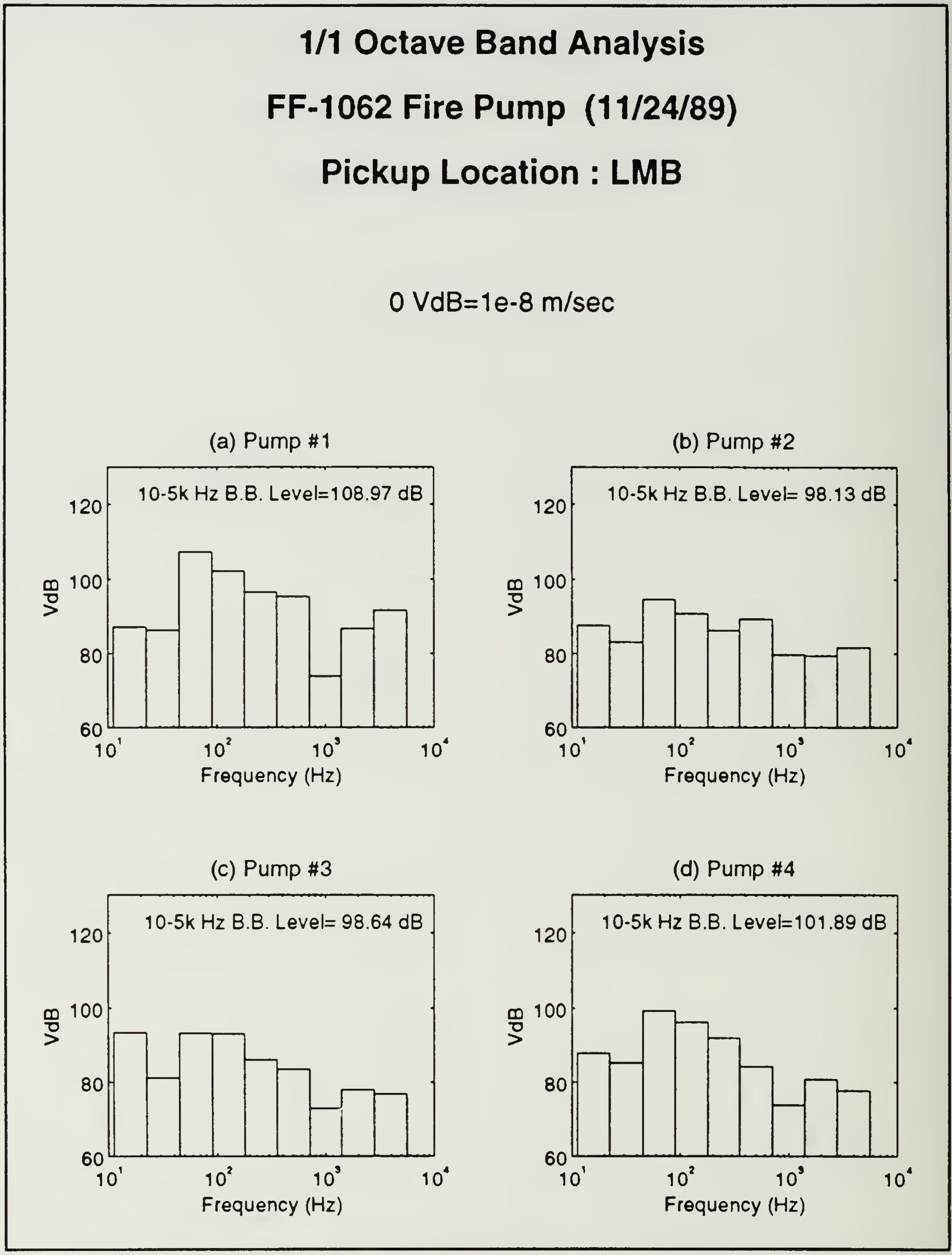


Figure E.18 The 1/1 Octave Band Analysis Results for FF-1062 (11/24/89) Fire Pumps Measured at LMB

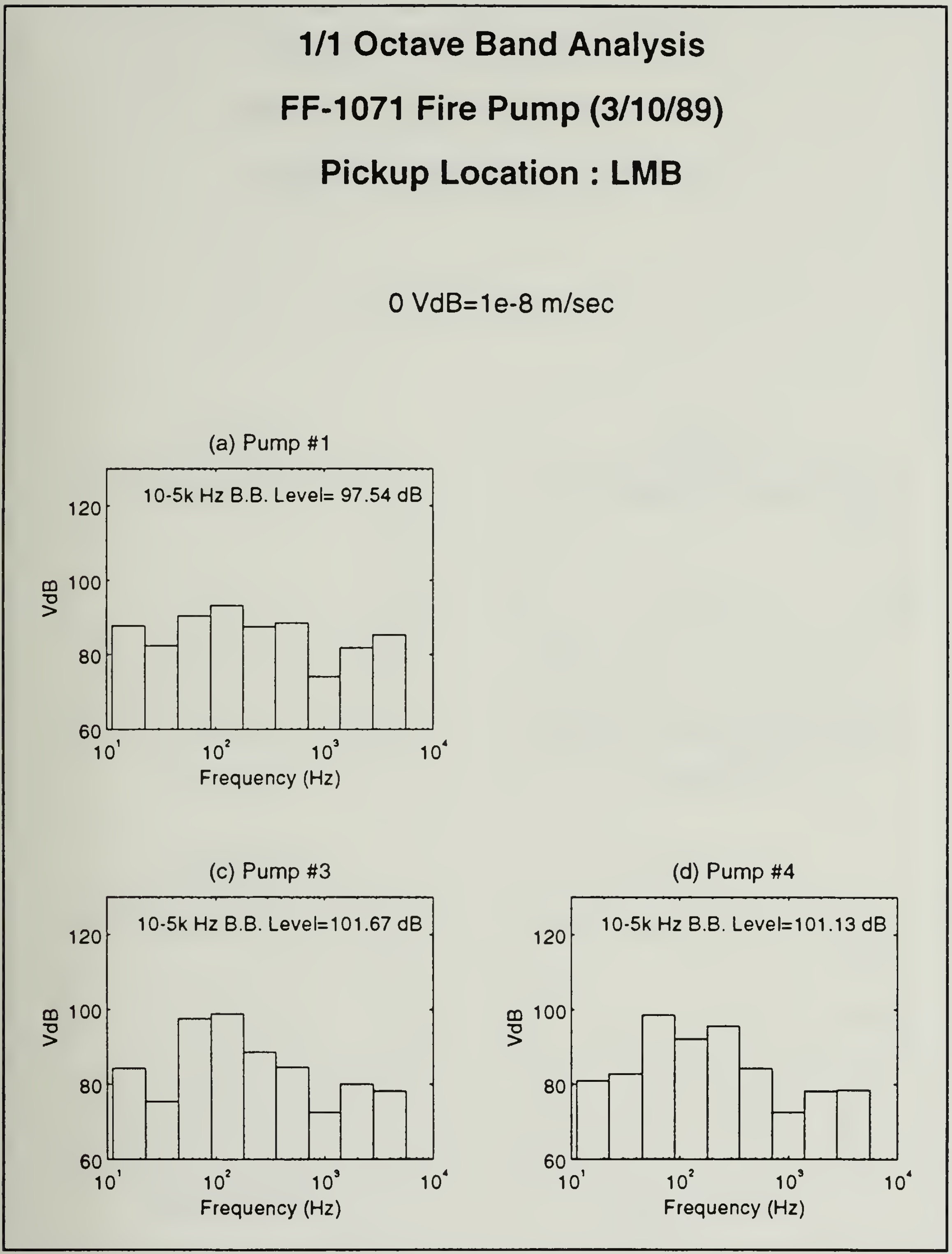


Figure E.19 The 1/1 Octave Band Analysis Results for FF-1071(3/10/89) Fire Pumps Measured at LMB

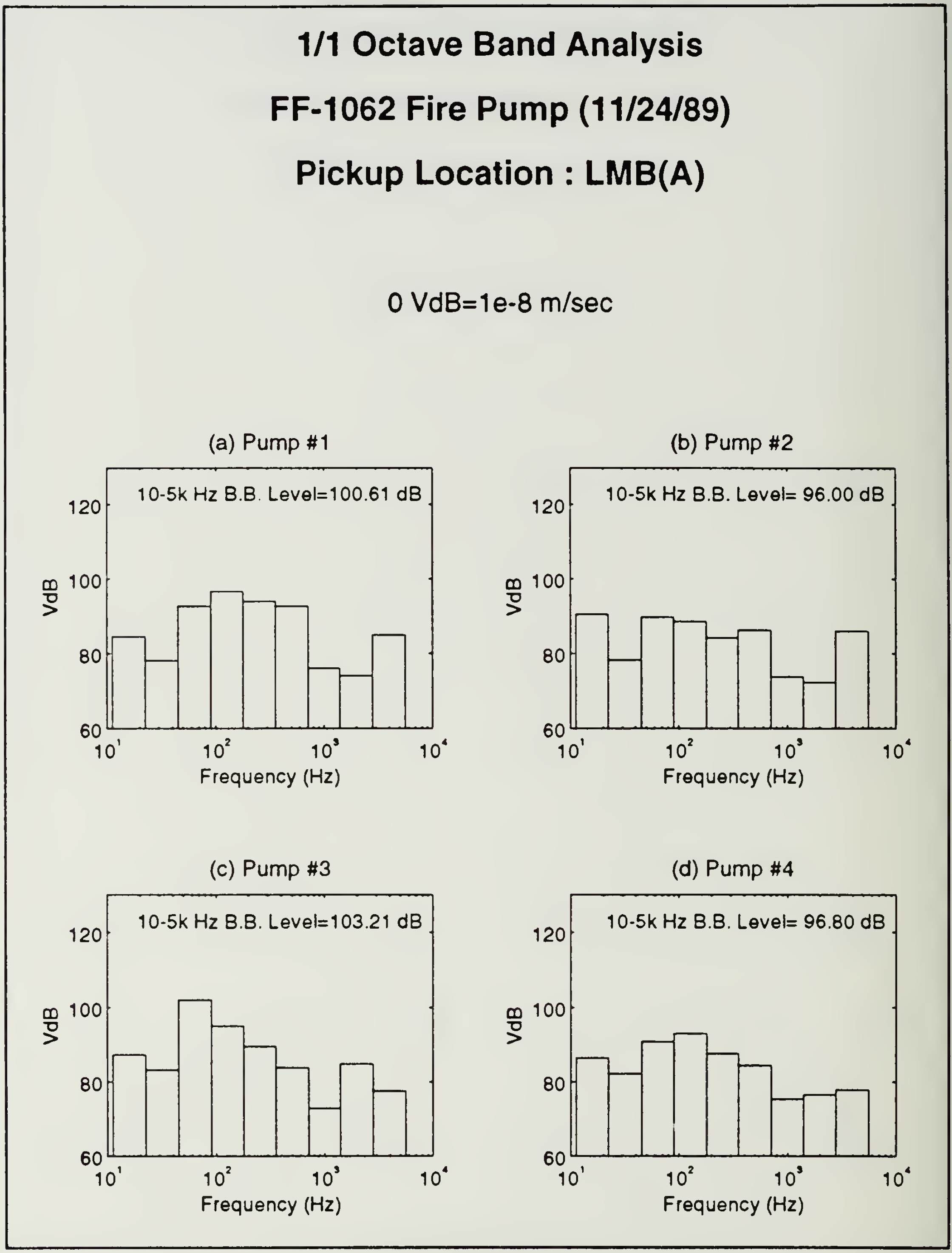


Figure E.20 The 1/1 Octave Band Analysis Results for FF-1062 (11/24/89) Fire Pumps Measured at LMB(A)

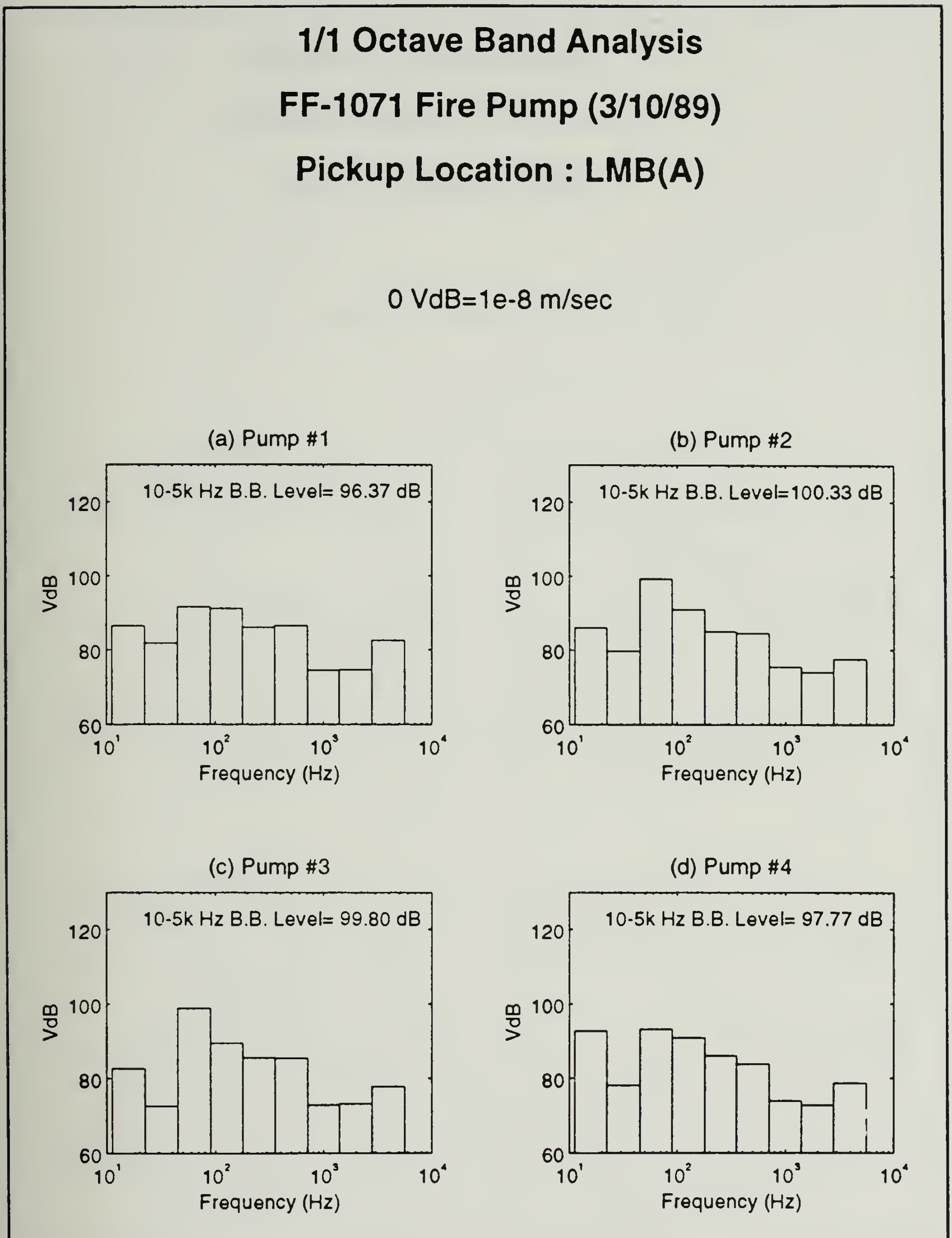


Figure E.21 The 1/1 Octave Band Analysis Results for FF-1071(3/10/89) Fire Pumps Measured at LMB(A)

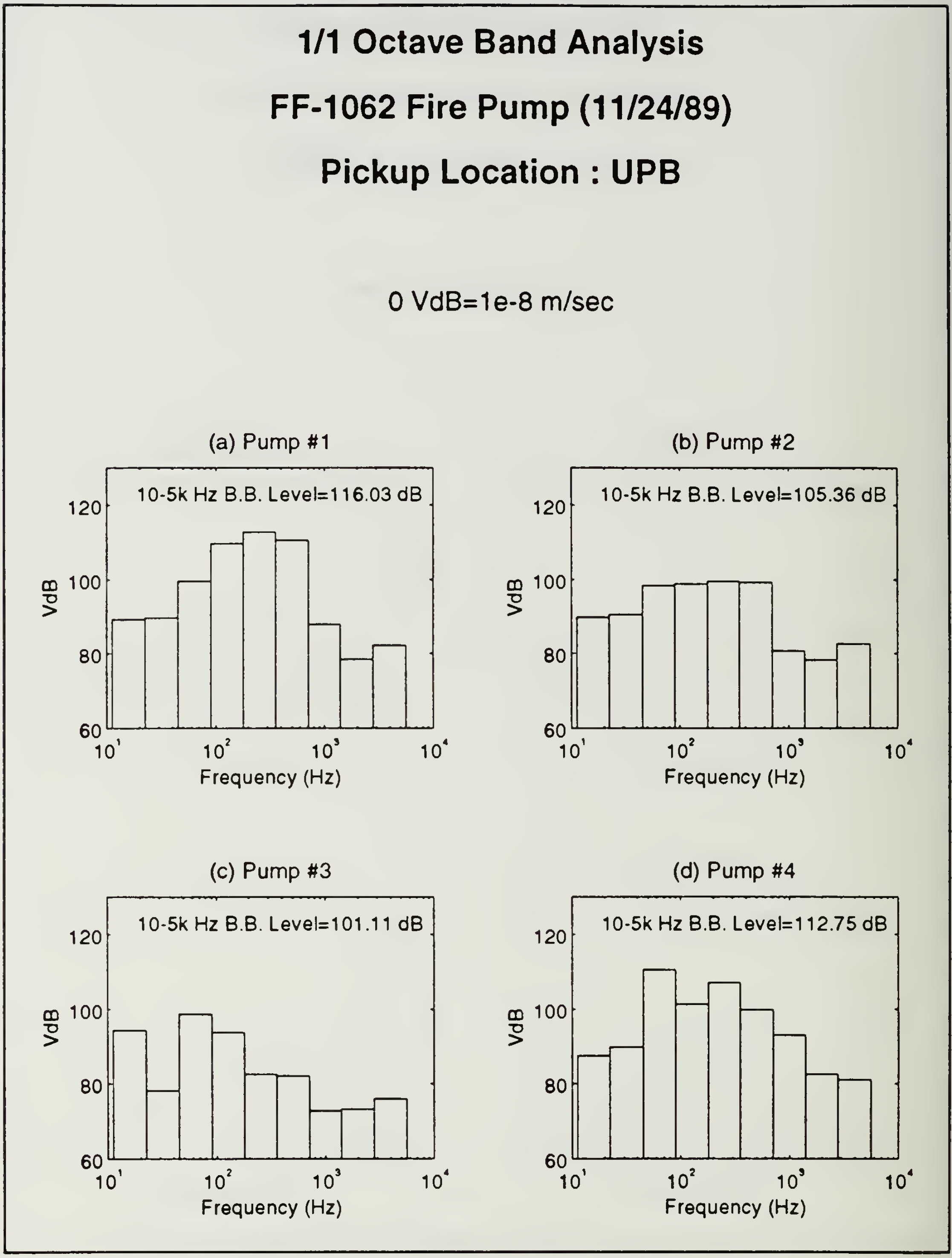


Figure E.22 The 1/1 Octave Band Analysis Results for FF-1062 (11/24/89) Fire Pumps Measured at UPB

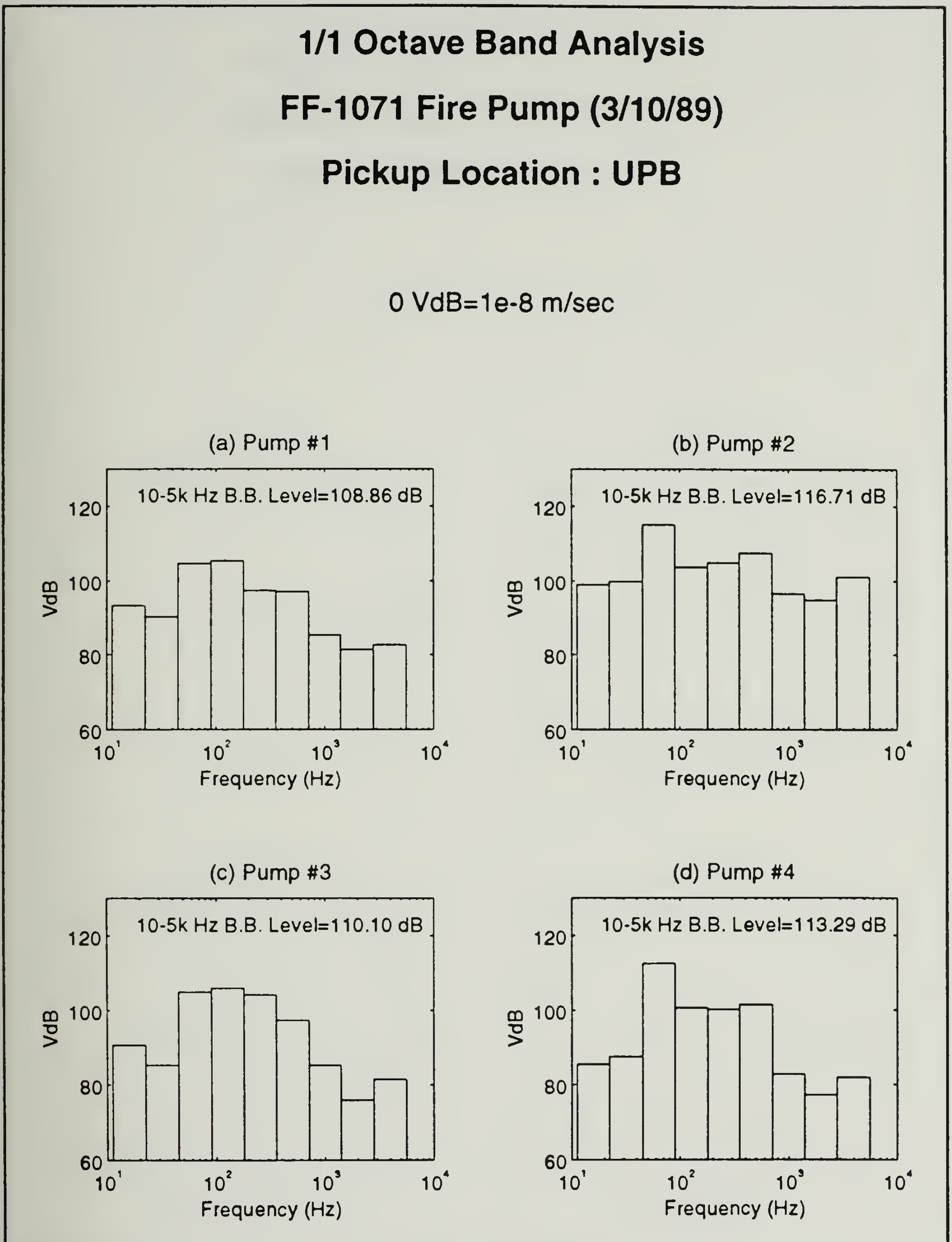


Figure E.23 The 1/1 Octave Band Analysis Results for FF-1071(3/10/89) Fire Pumps Measured at UPB

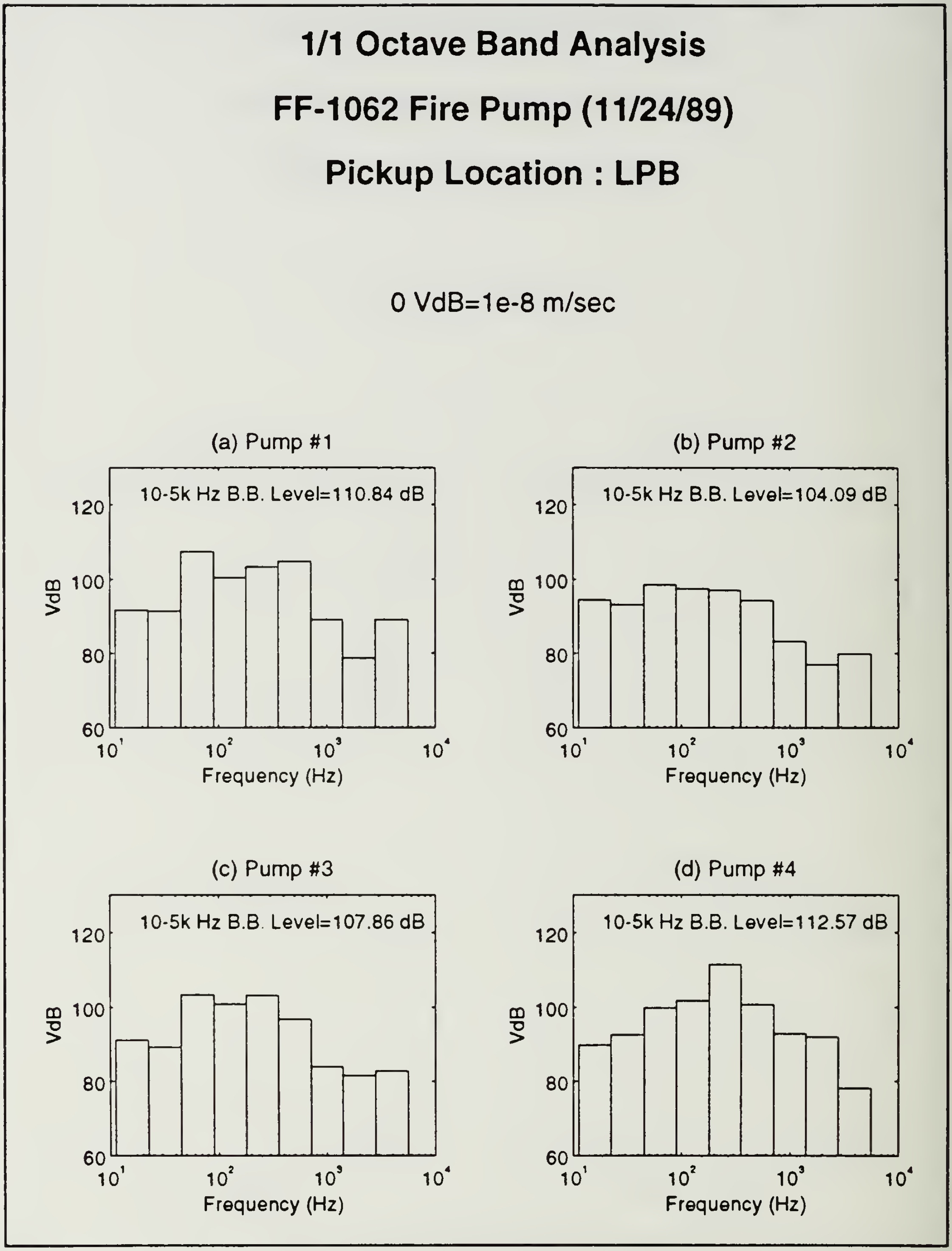


Figure E.24 The 1/1 Octave Band Analysis Results for FF-1062 (11/24/89) Fire Pumps Measured at LPB

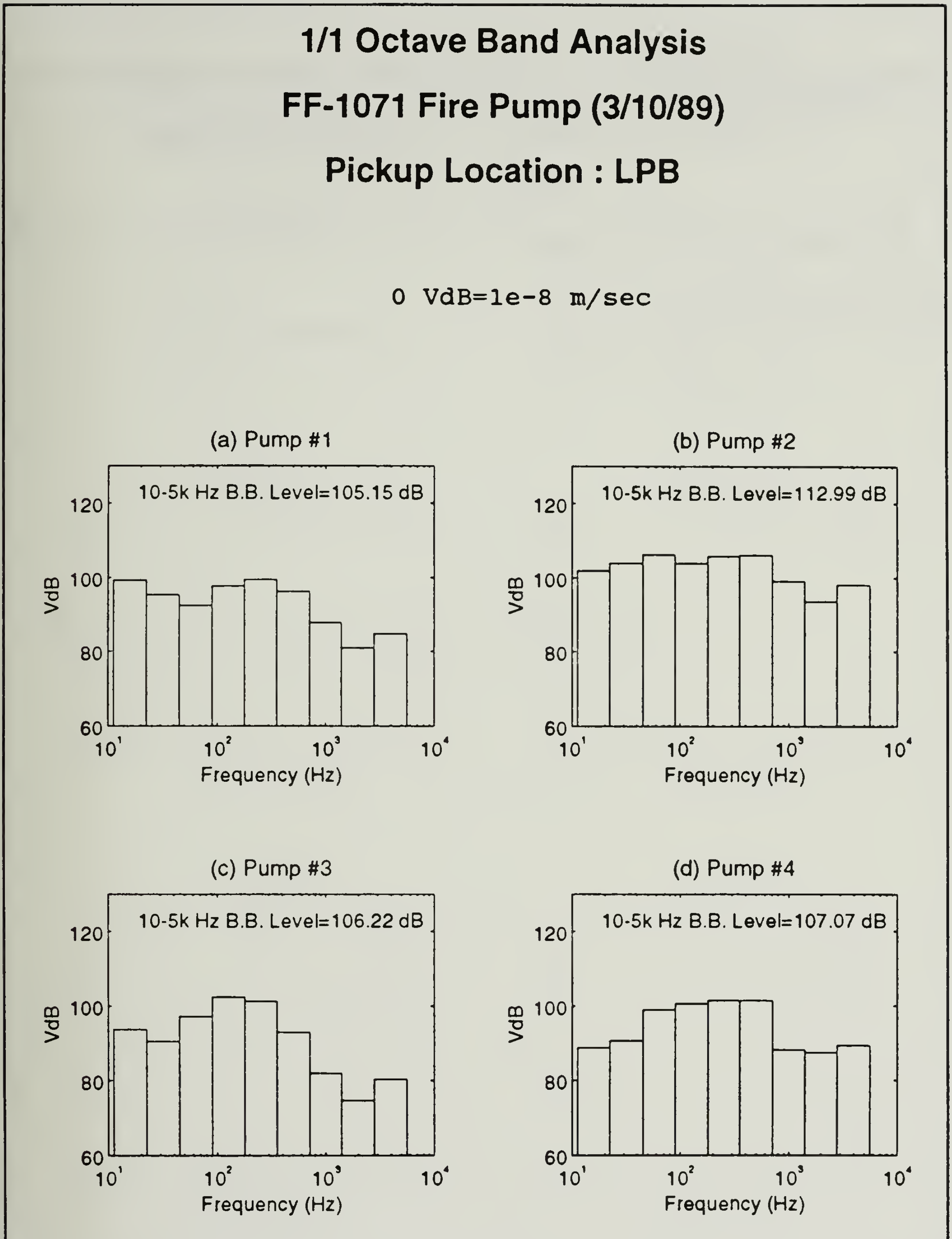


Figure E.25 The 1/1 Octave Band Analysis Results for FF-1071(3/10/89) Fire Pumps Measured at LPB

APPENDIX F. FIGURES OF 1/1 OCTAVE BAND LEVELS USING NAVSSES FREQUENCY DOMAIN DATABASE

This section contains all the figures of 1/1 octave band levels using NAVSSES frequency domain database.

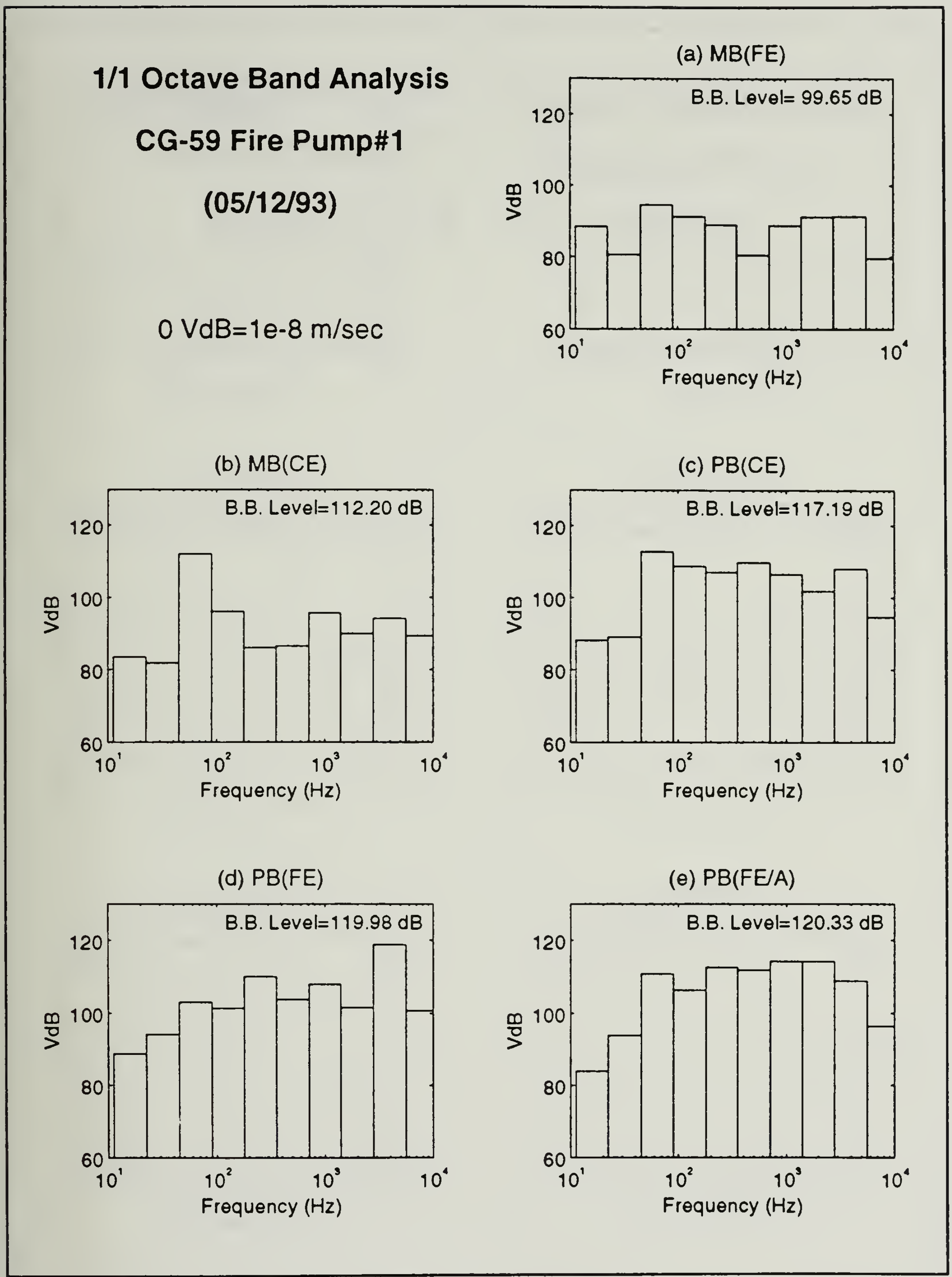


Figure F.1 The 1/1 Octave Band Analysis Results for CG-59 (05/12/93) Fire Pump#1

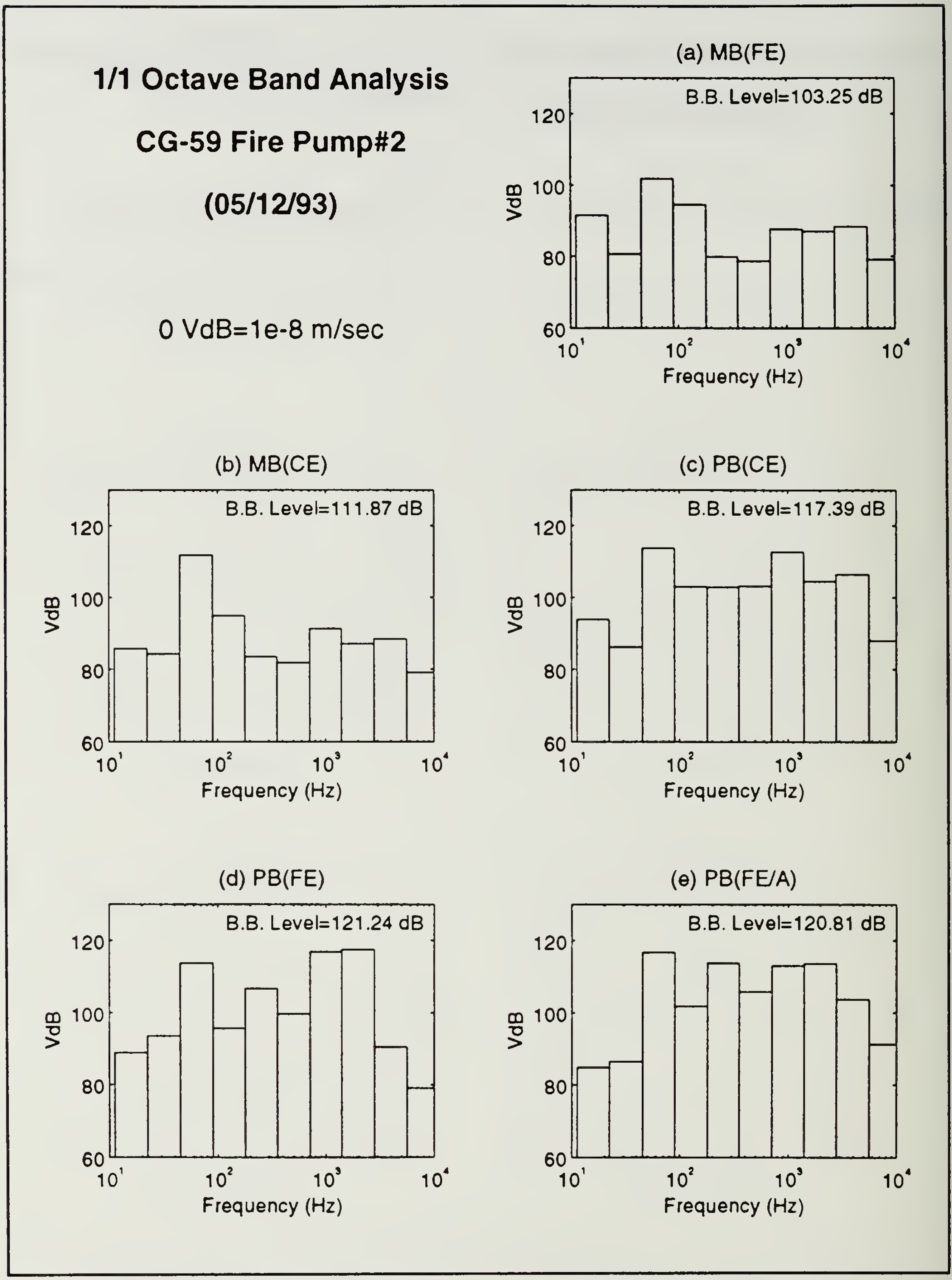


Figure F.2 The 1/1 Octave Band Analysis Results for CG-59 (05/12/93) Fire Pump#2

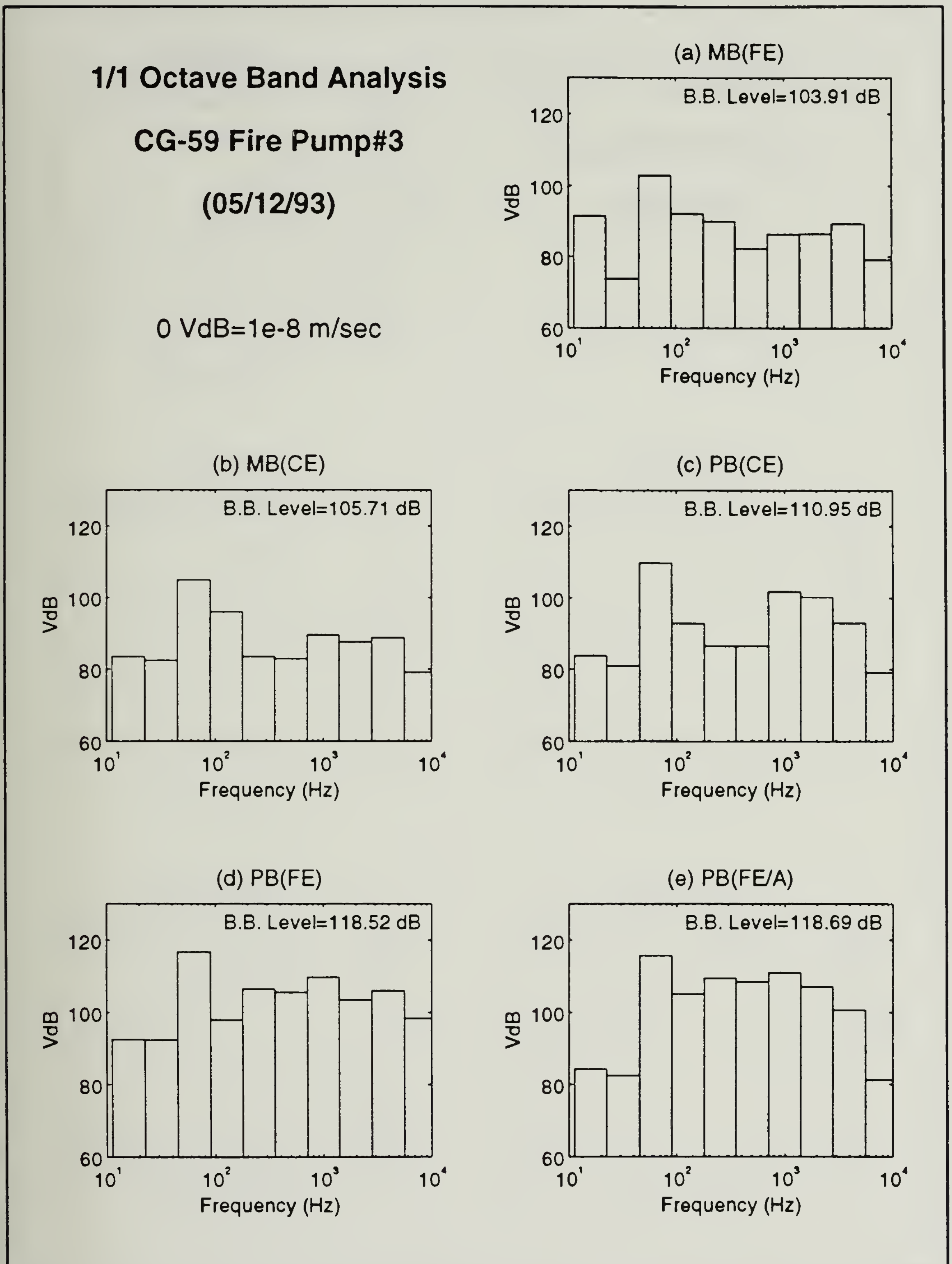


Figure F.3 The 1/1 Octave Band Analysis Results for CG-59 (05/12/93) Fire Pump#3

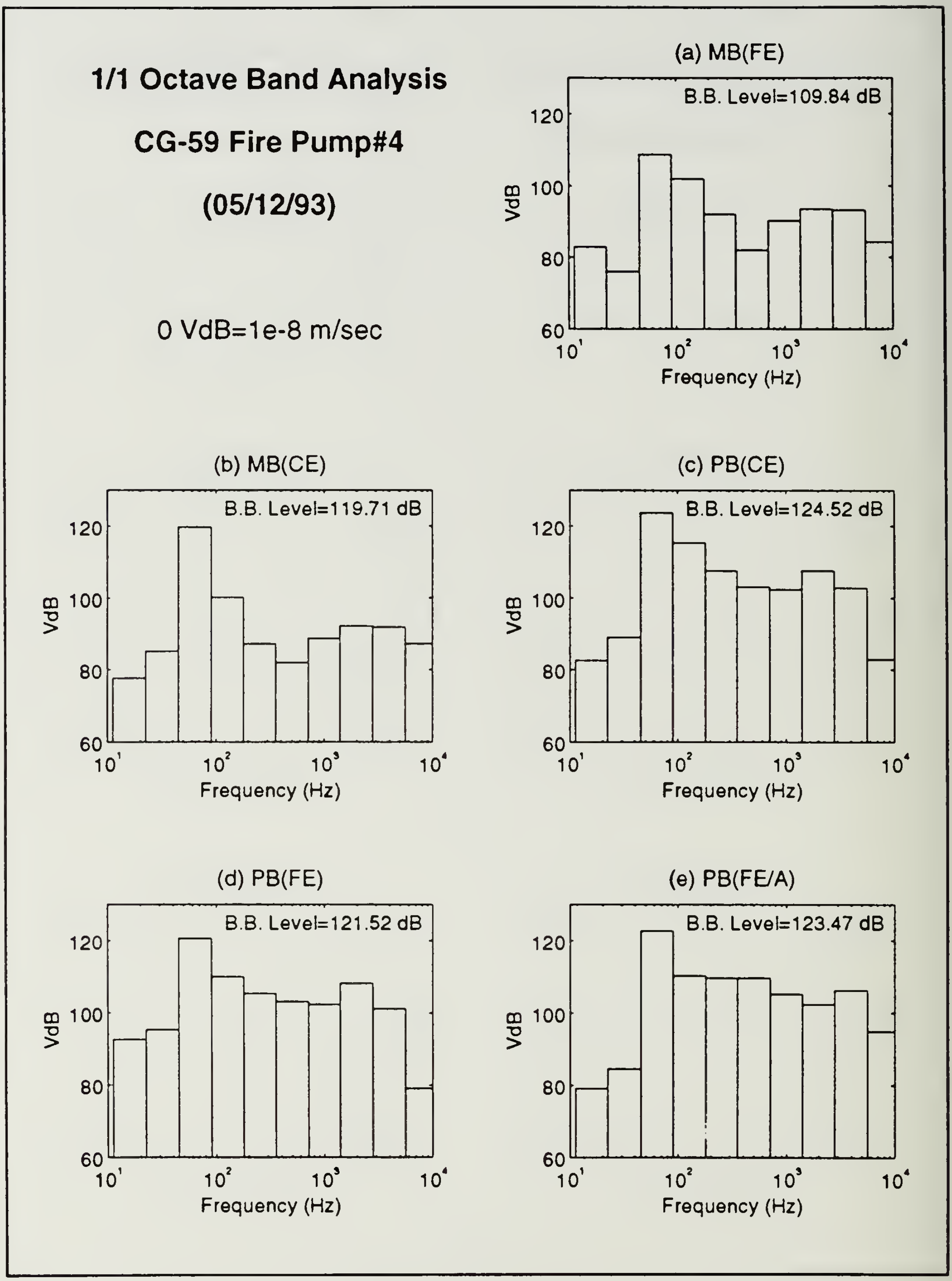


Figure F.4 The 1/1 Octave Band Analysis Results for CG-59 (05/12/93) Fire Pump#4

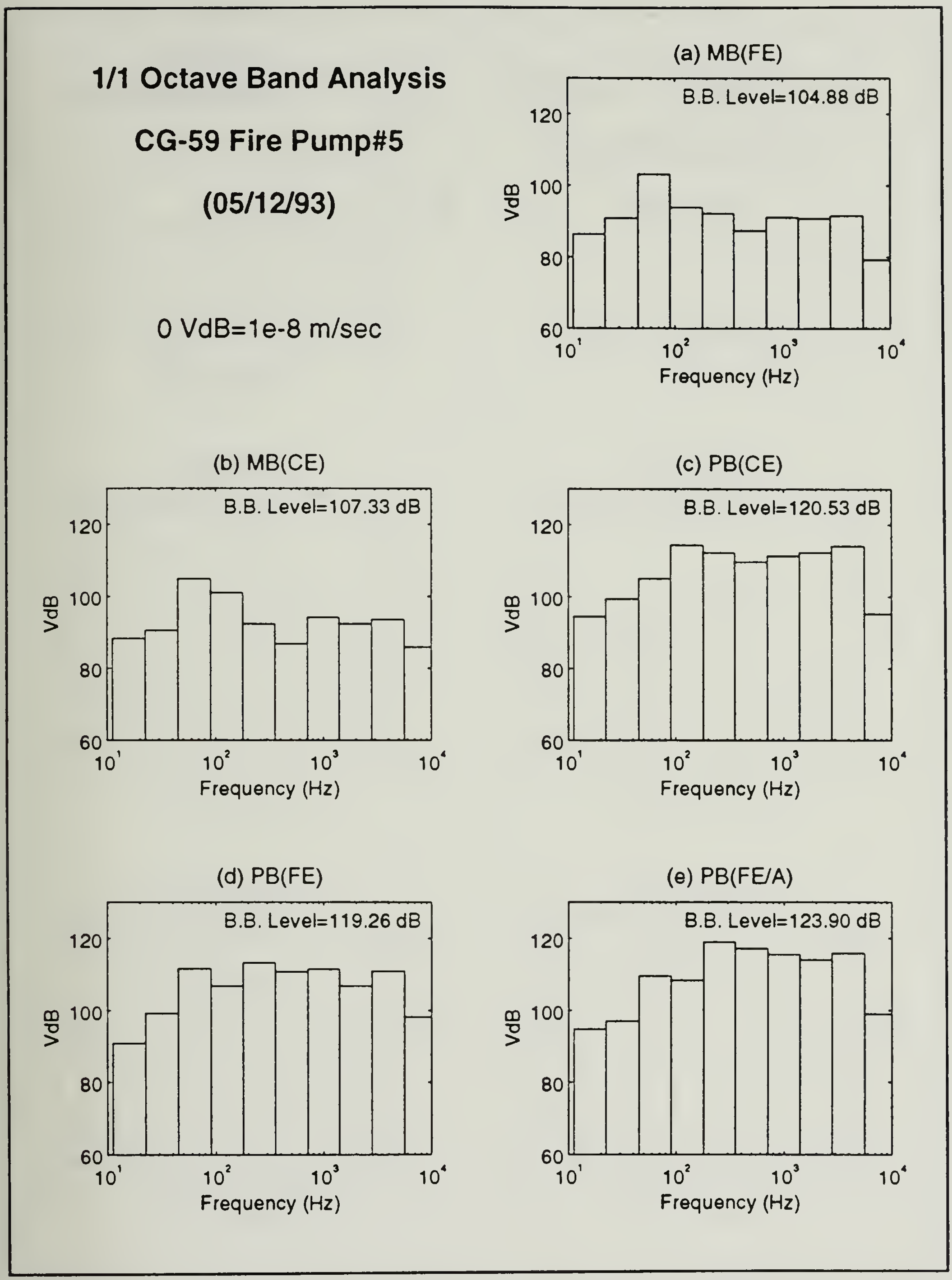


Figure F.5 The 1/1 Octave Band Analysis Results for CG-59 (05/12/93) Fire Pump#5

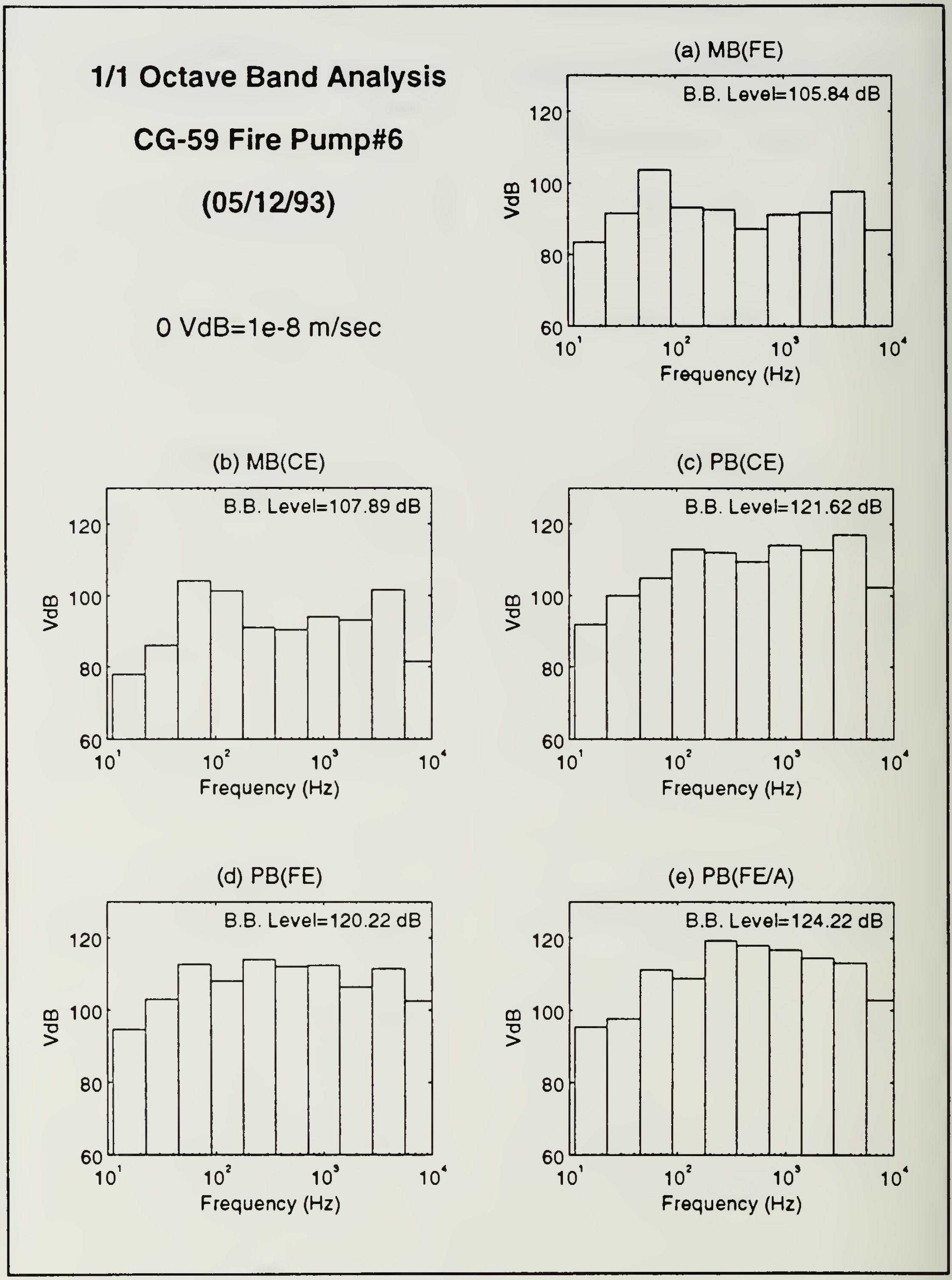


Figure F.6 The 1/1 Octave Band Analysis Results for CG-59 (05/12/93) Fire Pump#6

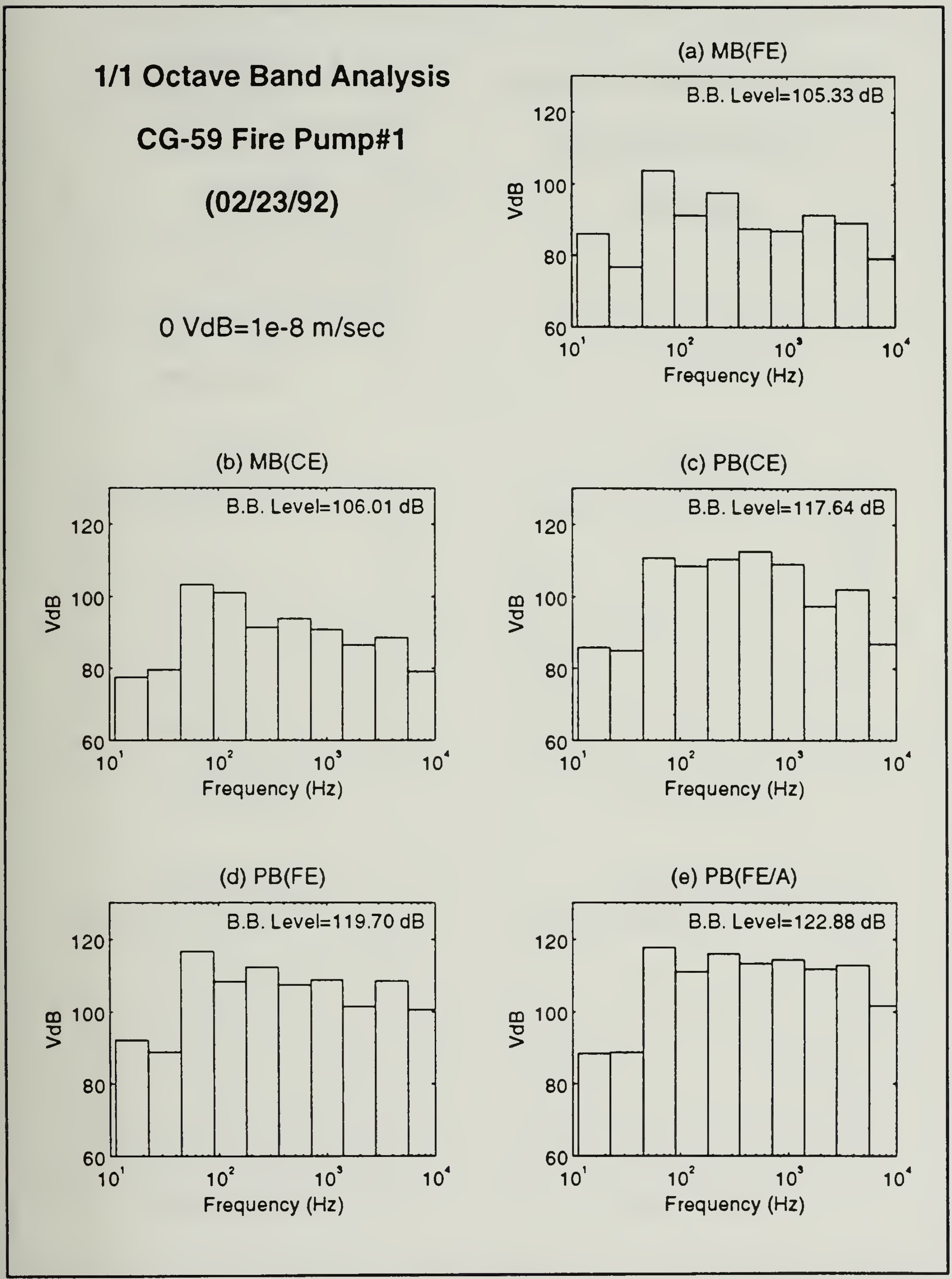


Figure F.7 The 1/1 Octave Band Analysis Results for CG-59 (02/23/92) Fire Pump#1

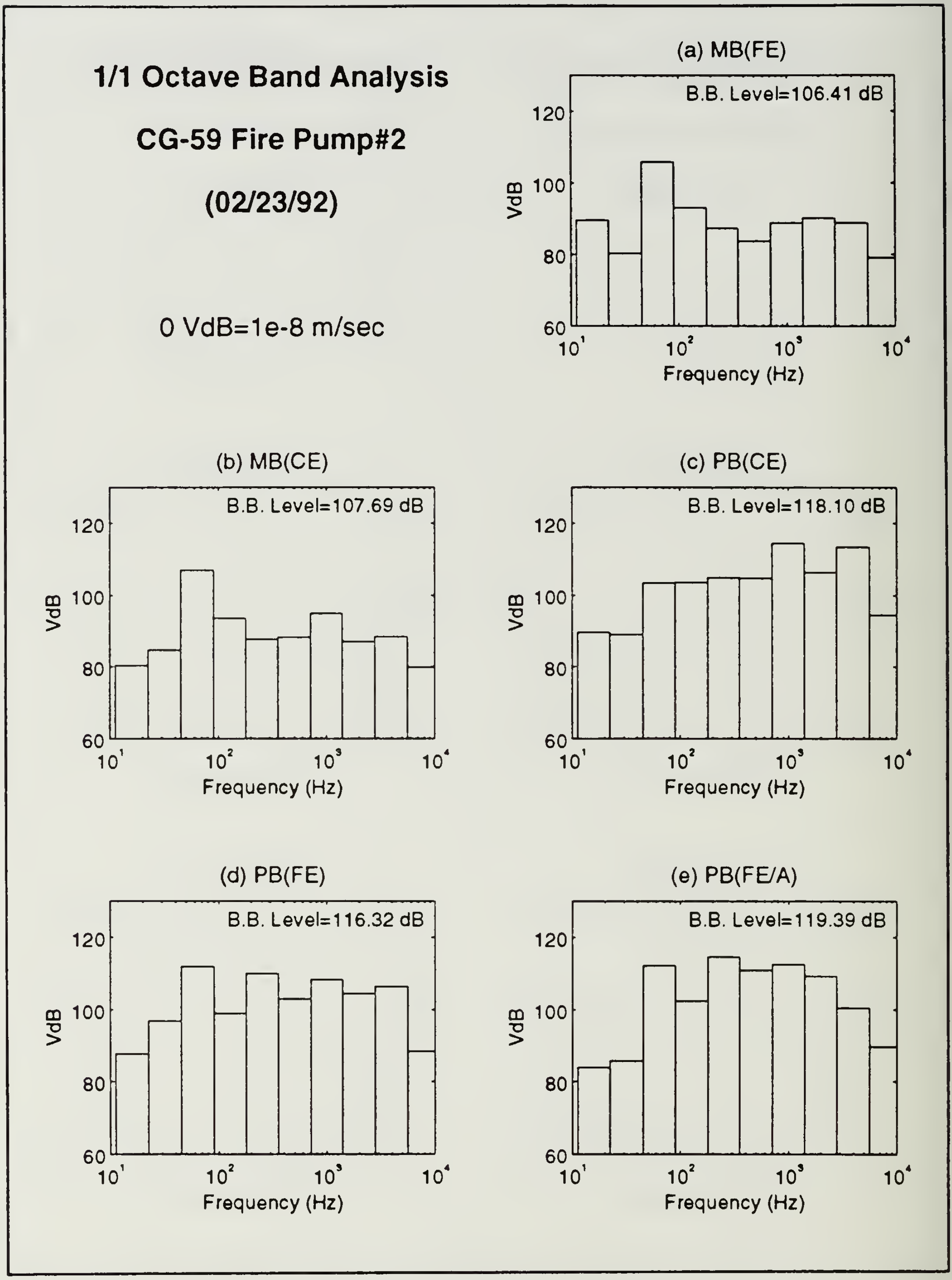


Figure F.8 The 1/1 Octave Band Analysis Results for CG-59 (02/23/92) Fire Pump#2

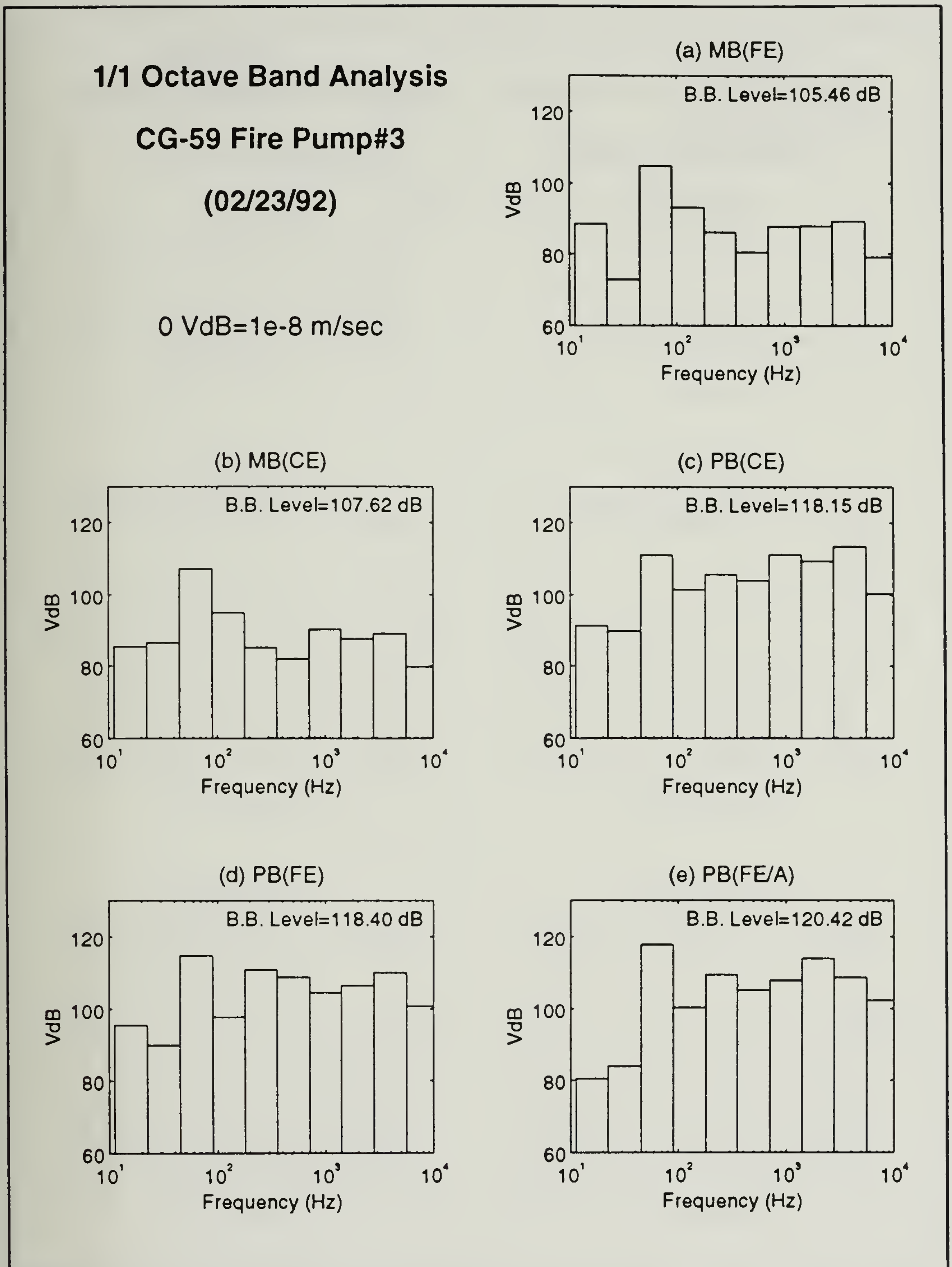


Figure F.9 The 1/1 Octave Band Analysis Results for CG-59 (02/23/92) Fire Pump#3

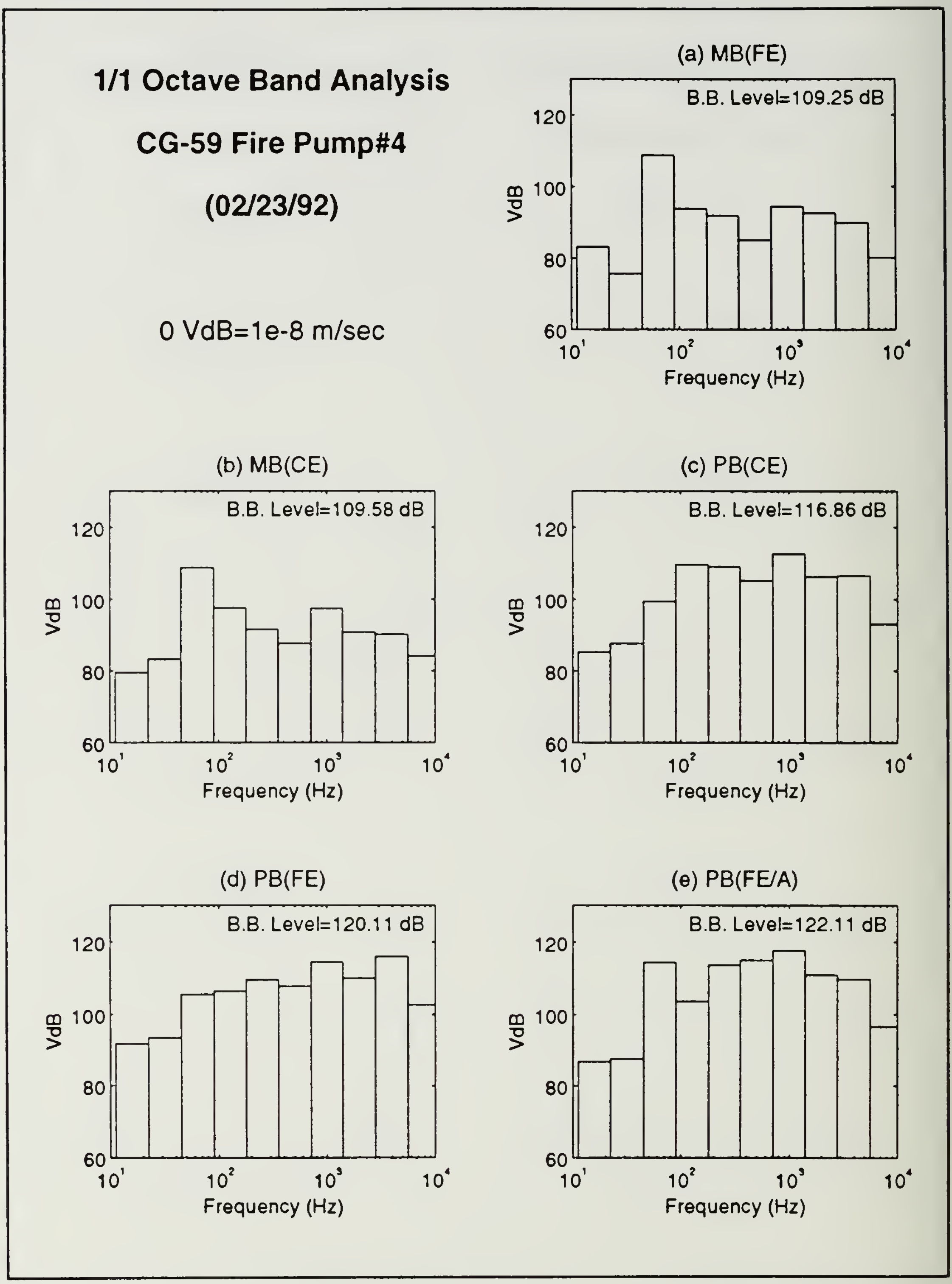


Figure F.10 The 1/1 Octave Band Analysis Results for CG-59 (02/23/92) Fire Pump#4

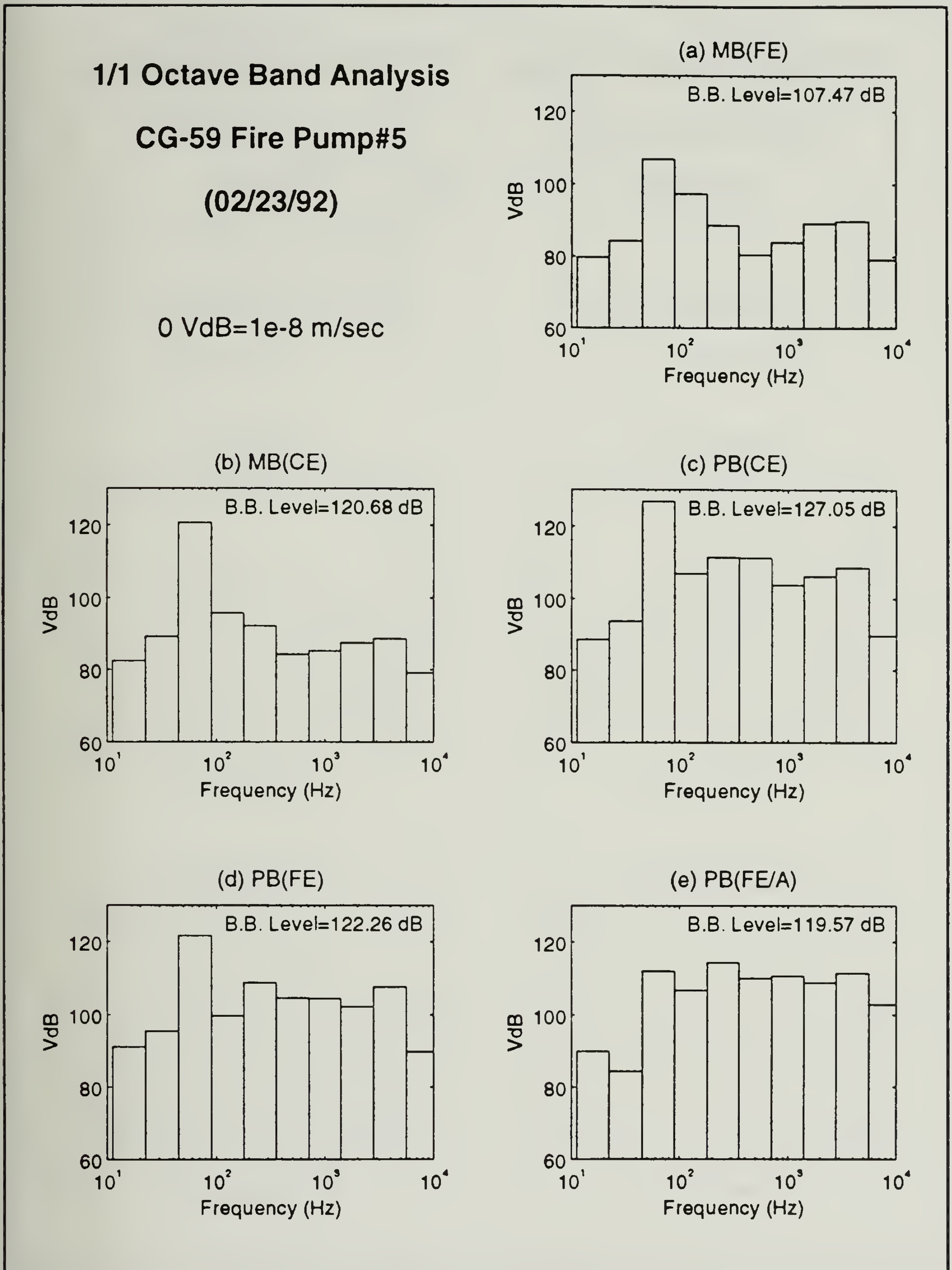


Figure F.11 The 1/1 Octave Band Analysis Results for CG-59 (02/23/92) Fire Pump#5

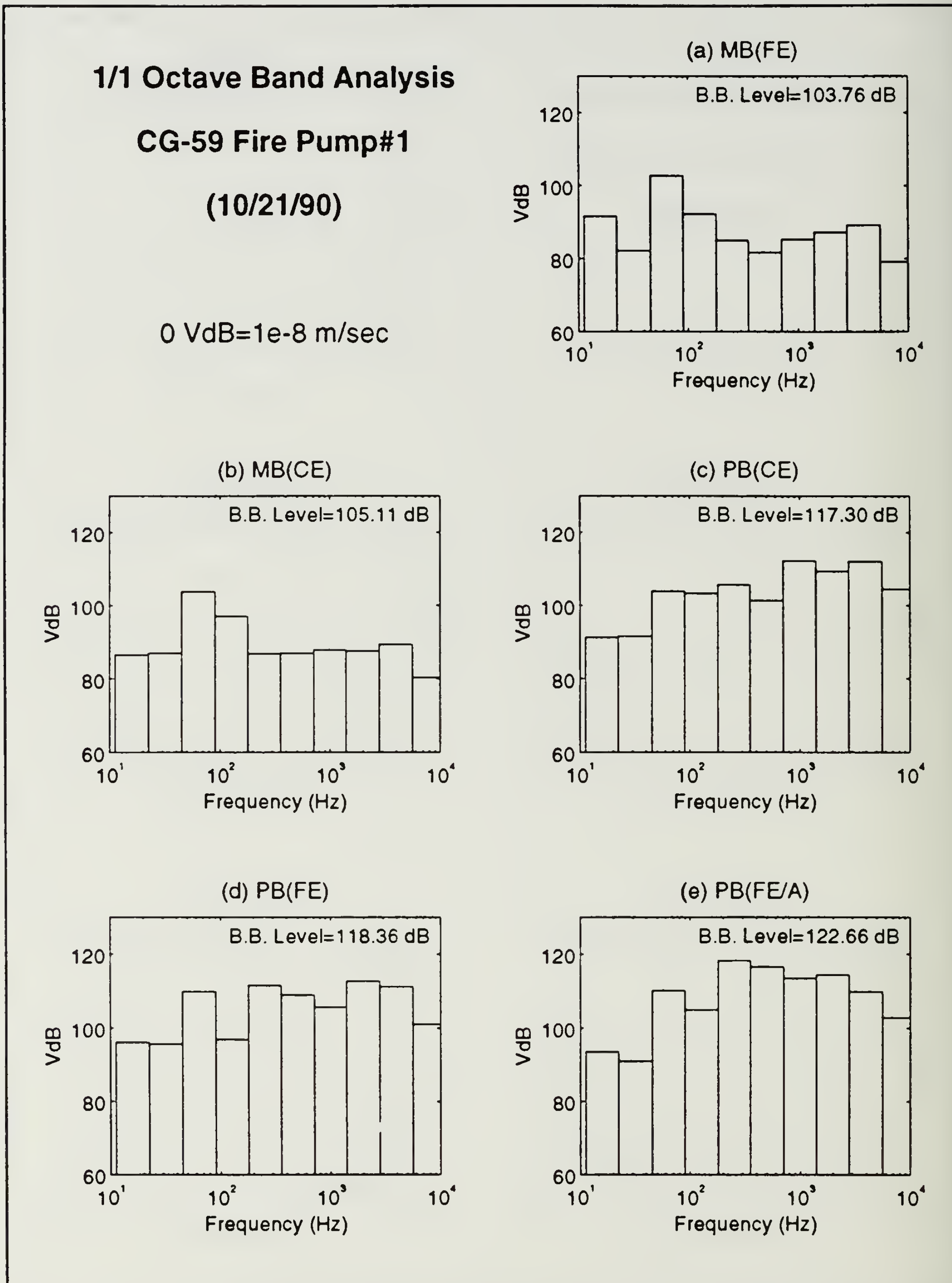


Figure F.12 The 1/1 Octave Band Analysis Results for CG-59 (10/21/90) Fire Pump#1

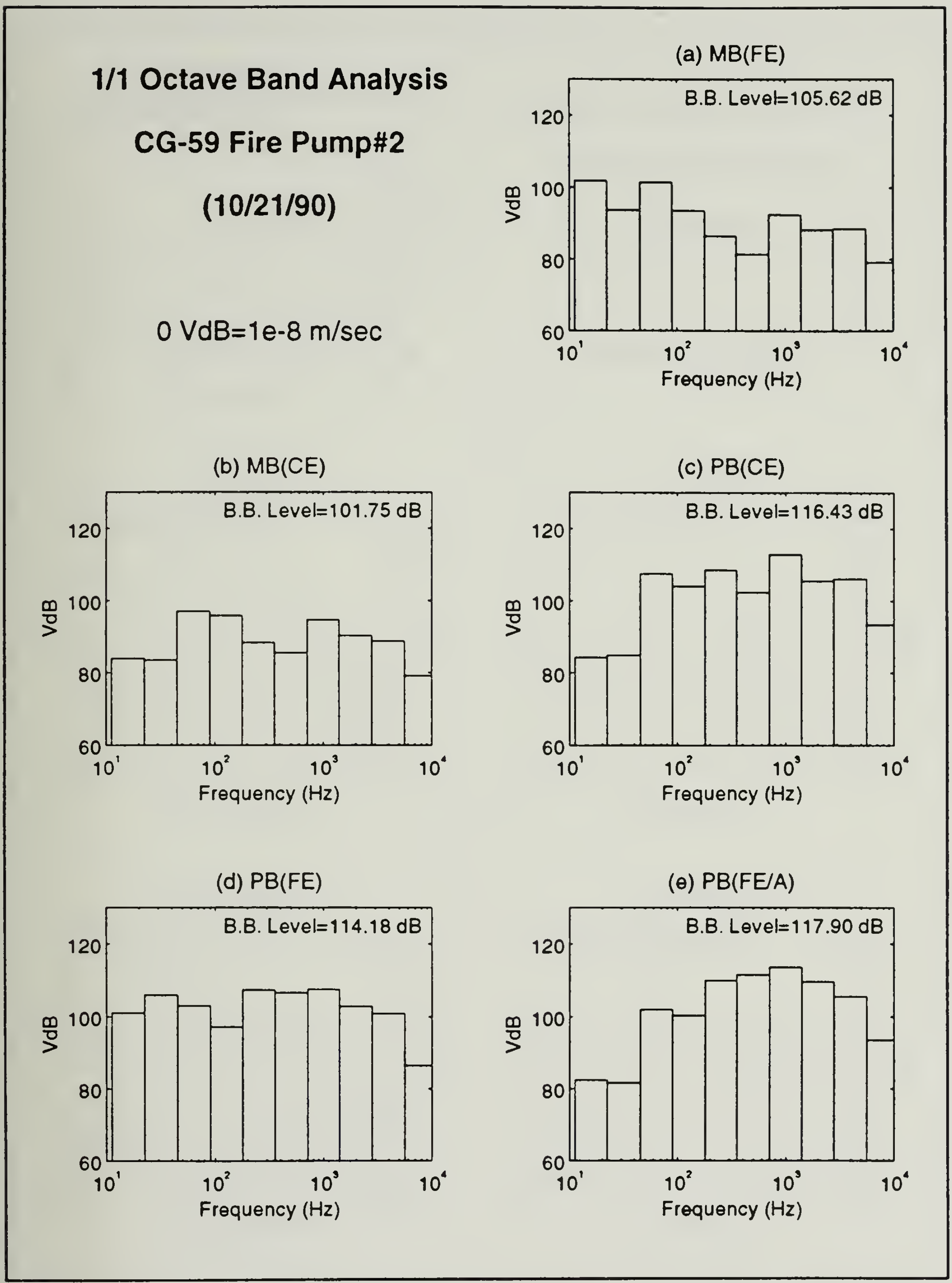


Figure F.13 The 1/1 Octave Band Analysis Results for CG-59 (10/21/90) Fire Pump#2

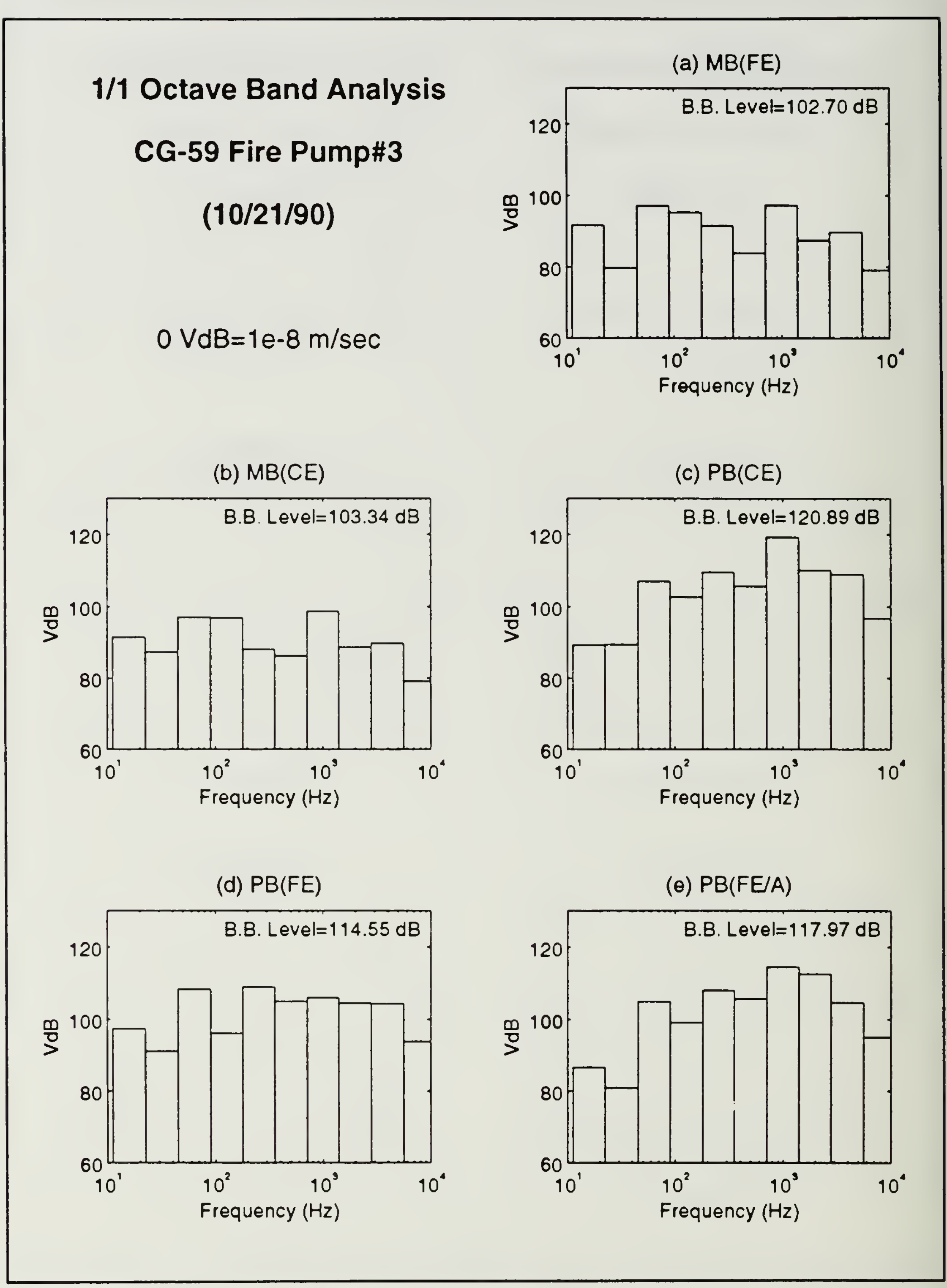


Figure F.14 The 1/1 Octave Band Analysis Results for CG-59 (10/21/90) Fire Pump#3

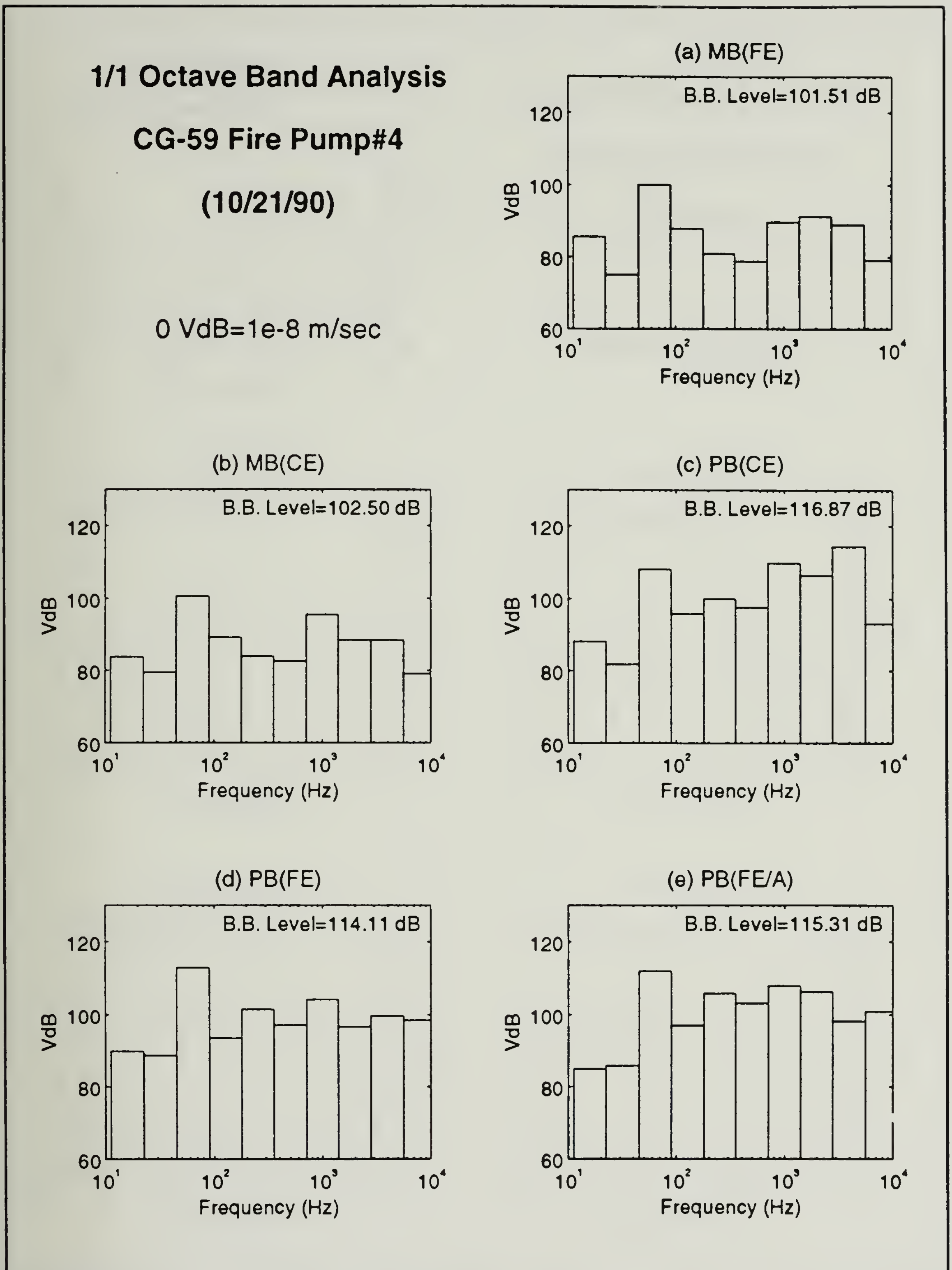


Figure F.15 The 1/1 Octave Band Analysis Results for CG-59 (10/21/90) Fire Pump#4

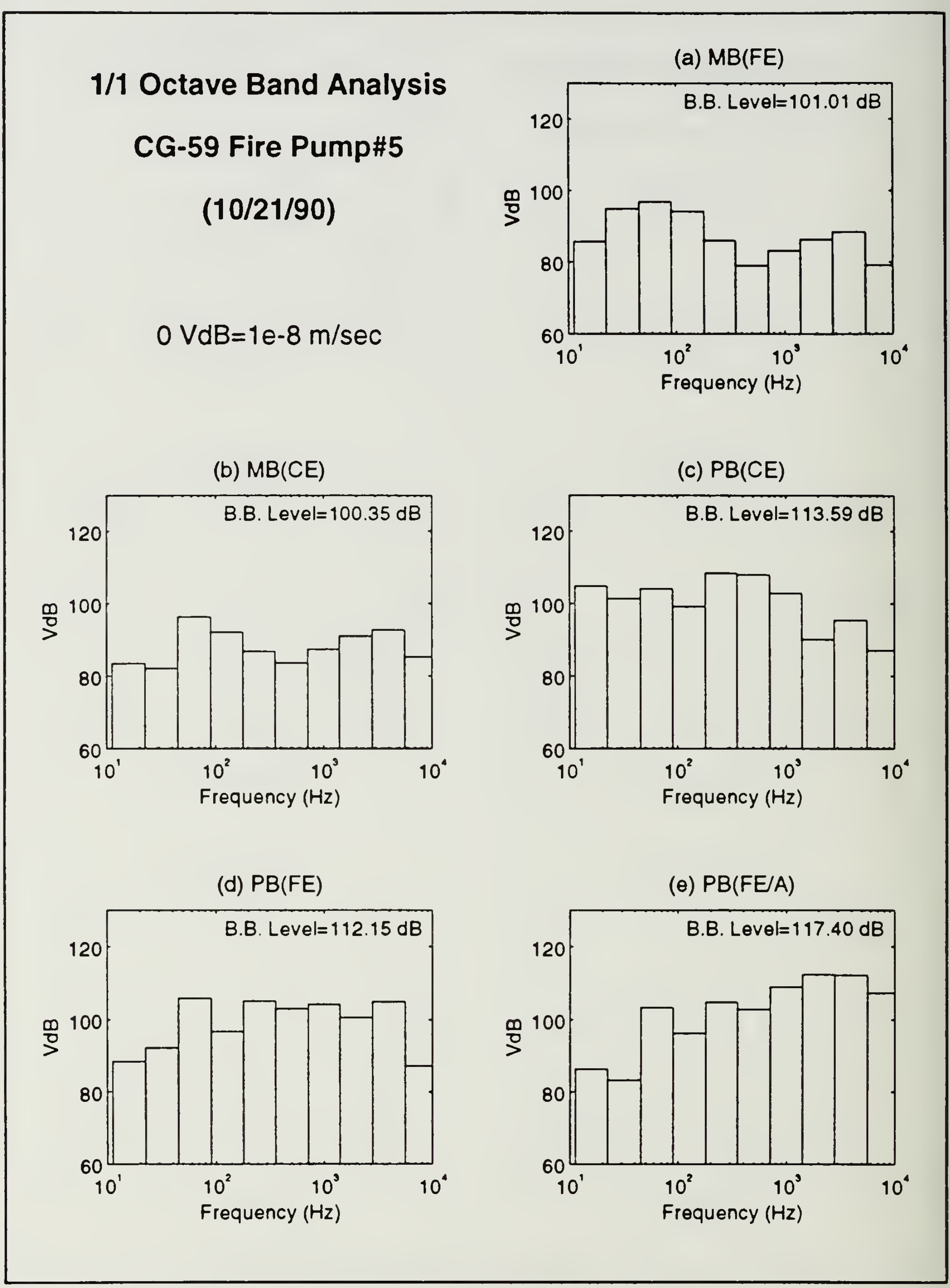


Figure F.16 The 1/1 Octave Band Analysis Results for CG-59 (10/21/90) Fire Pump#5

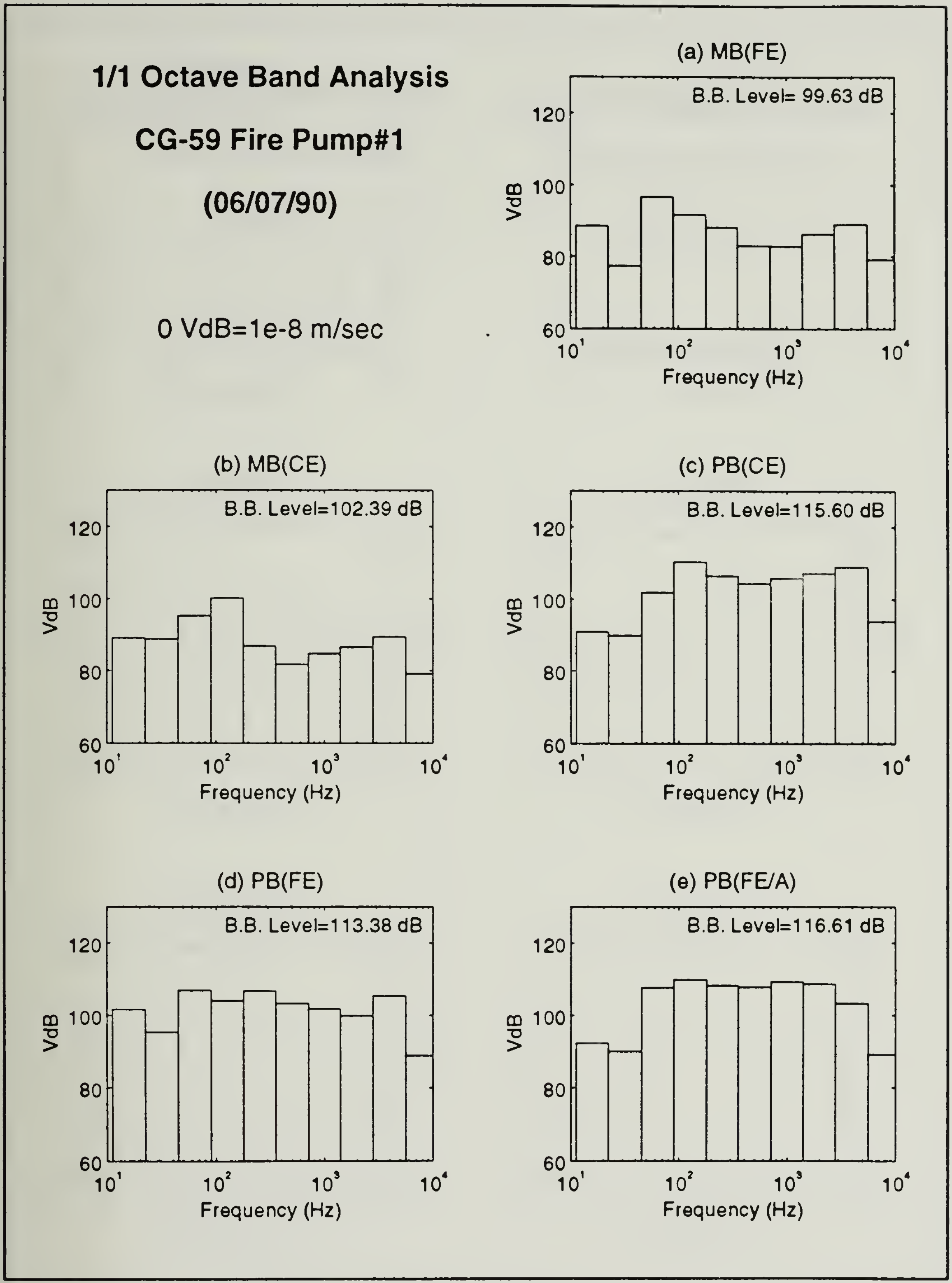


Figure F.17 The 1/1 Octave Band Analysis Results for CG-59 (06/07/90) Fire Pump#1

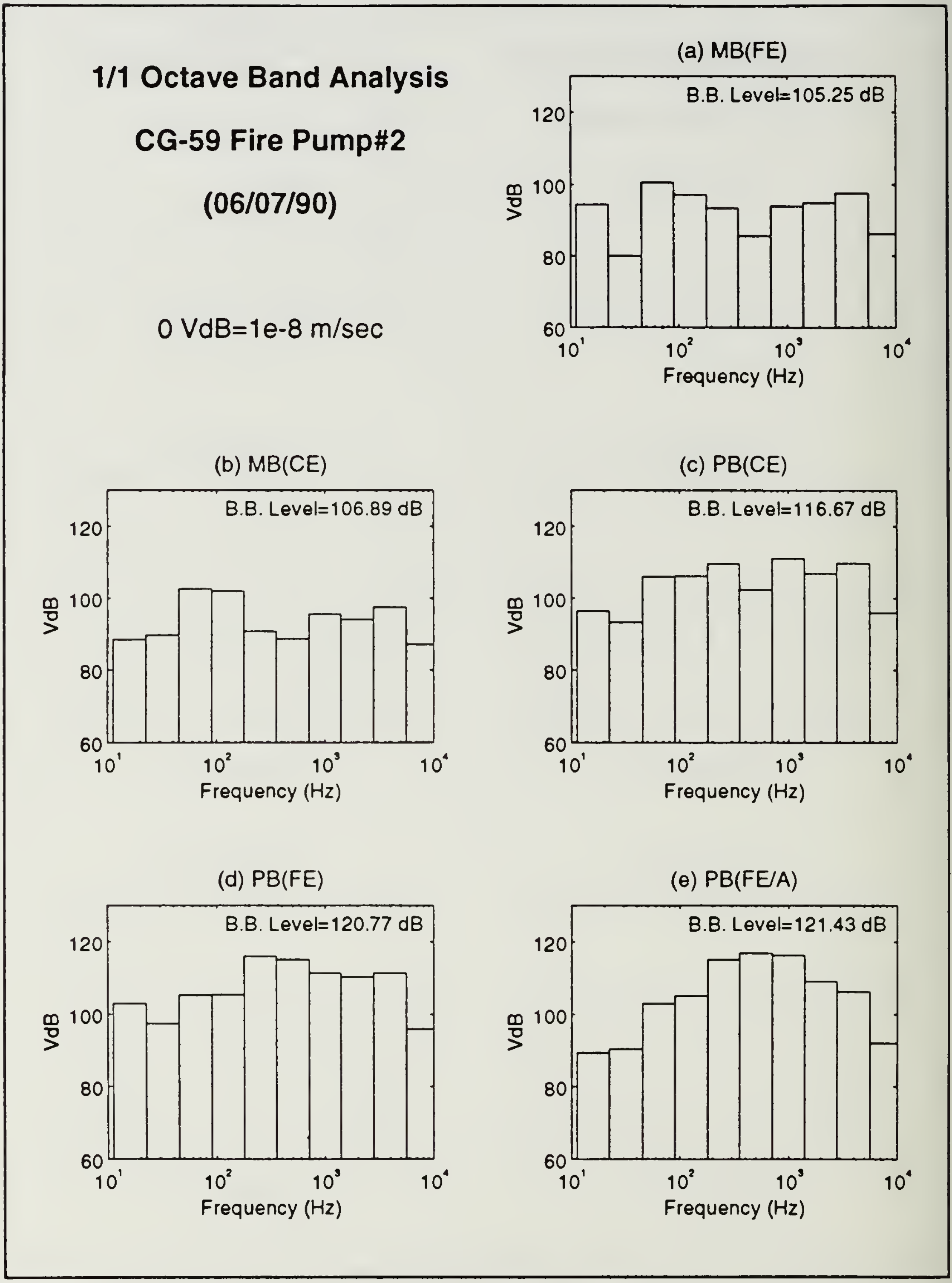


Figure F.18 The 1/1 Octave Band Analysis Results for CG-59 (06/07/90) Fire Pump#2

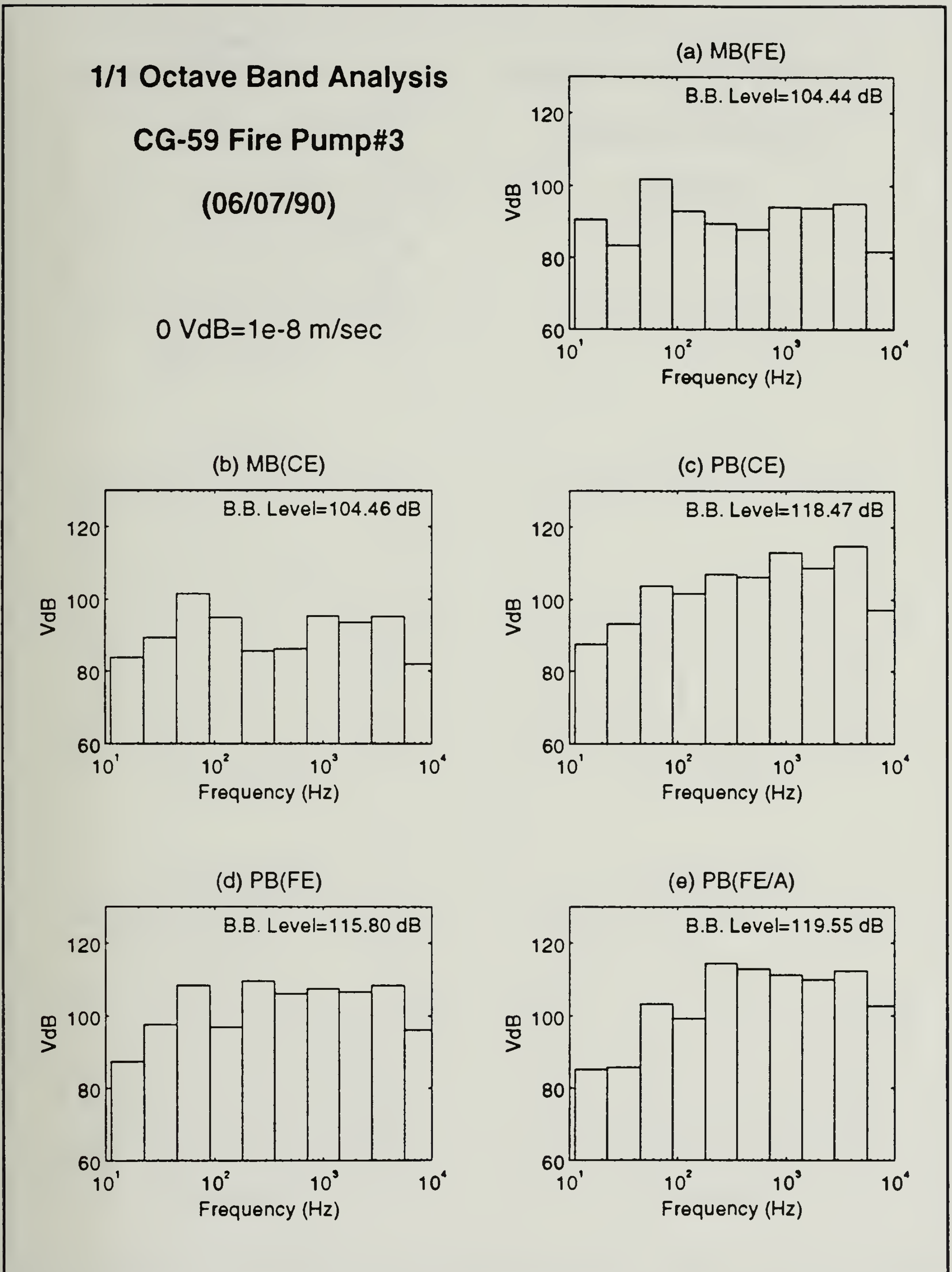


Figure F.19 The 1/1 Octave Band Analysis Results for CG-59 (06/07/90) Fire Pump#3

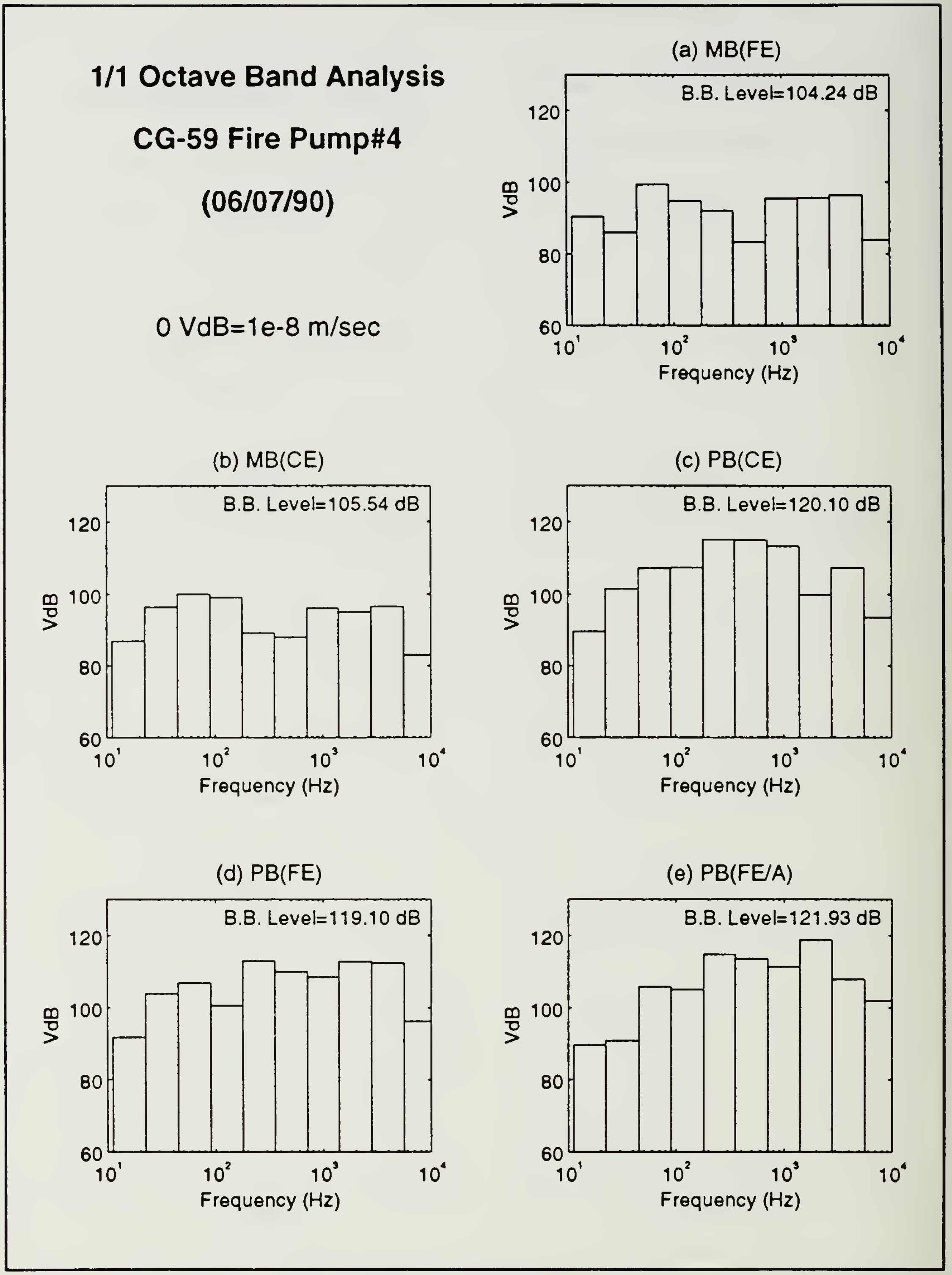


Figure F.20 The 1/1 Octave Band Analysis Results for CG-59 (06/07/90) Fire Pump#4

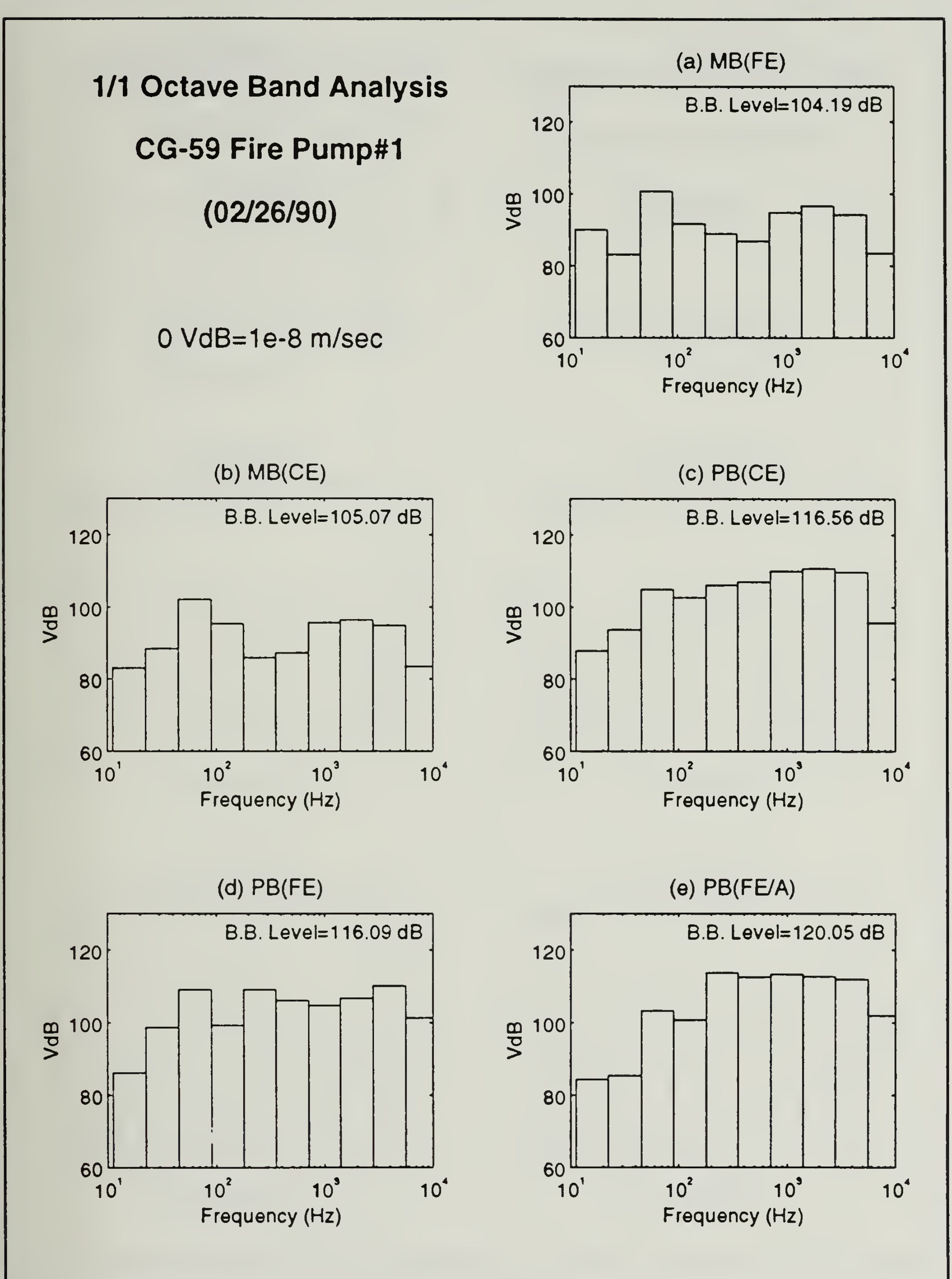


Figure F.21 The 1/1 Octave Band Analysis Results for CG-59 (02/26/90) Fire Pump#1

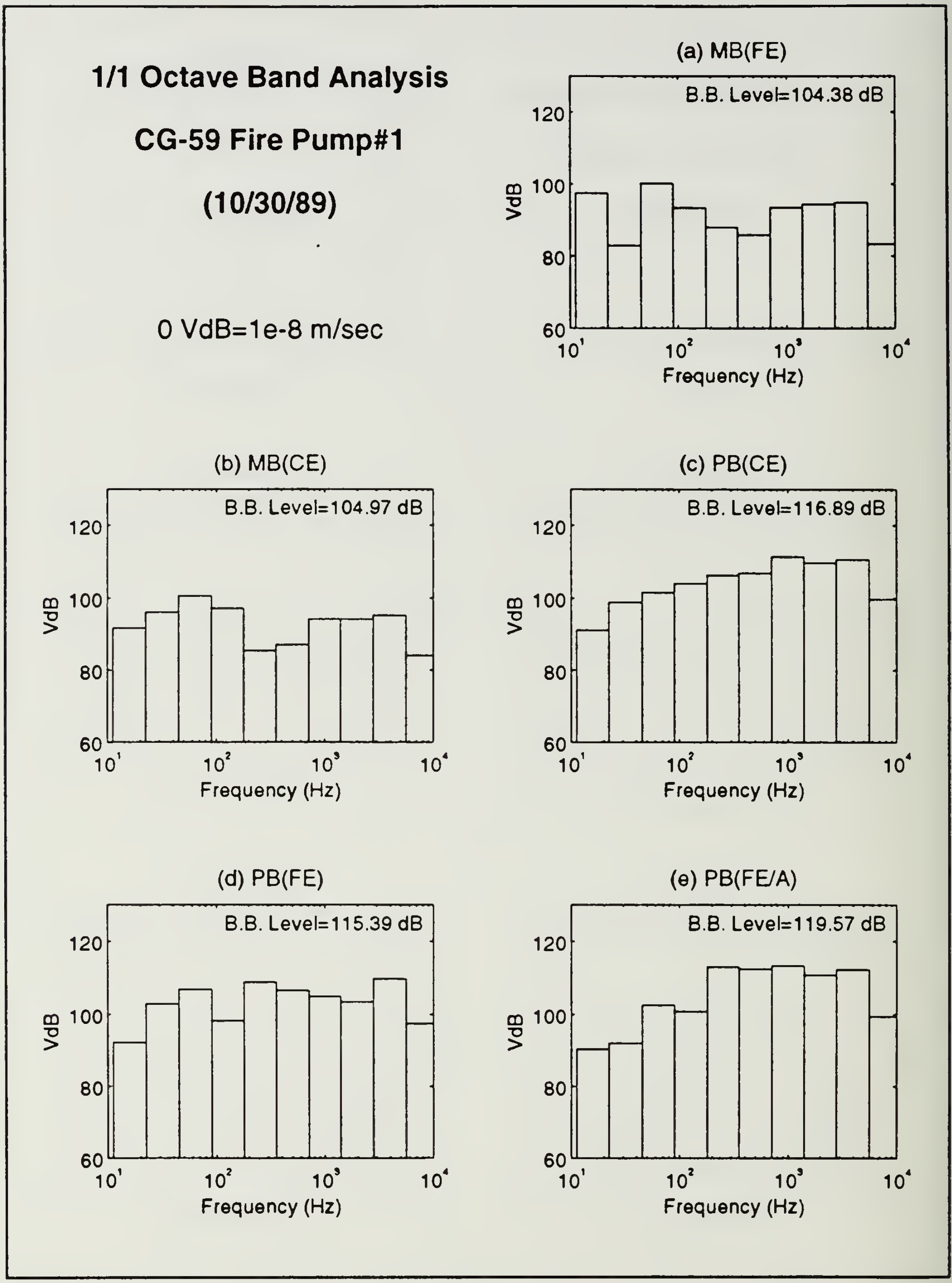


Figure F.22 The 1/1 Octave Band Analysis Results for CG-59 (10/30/89) Fire Pump#1

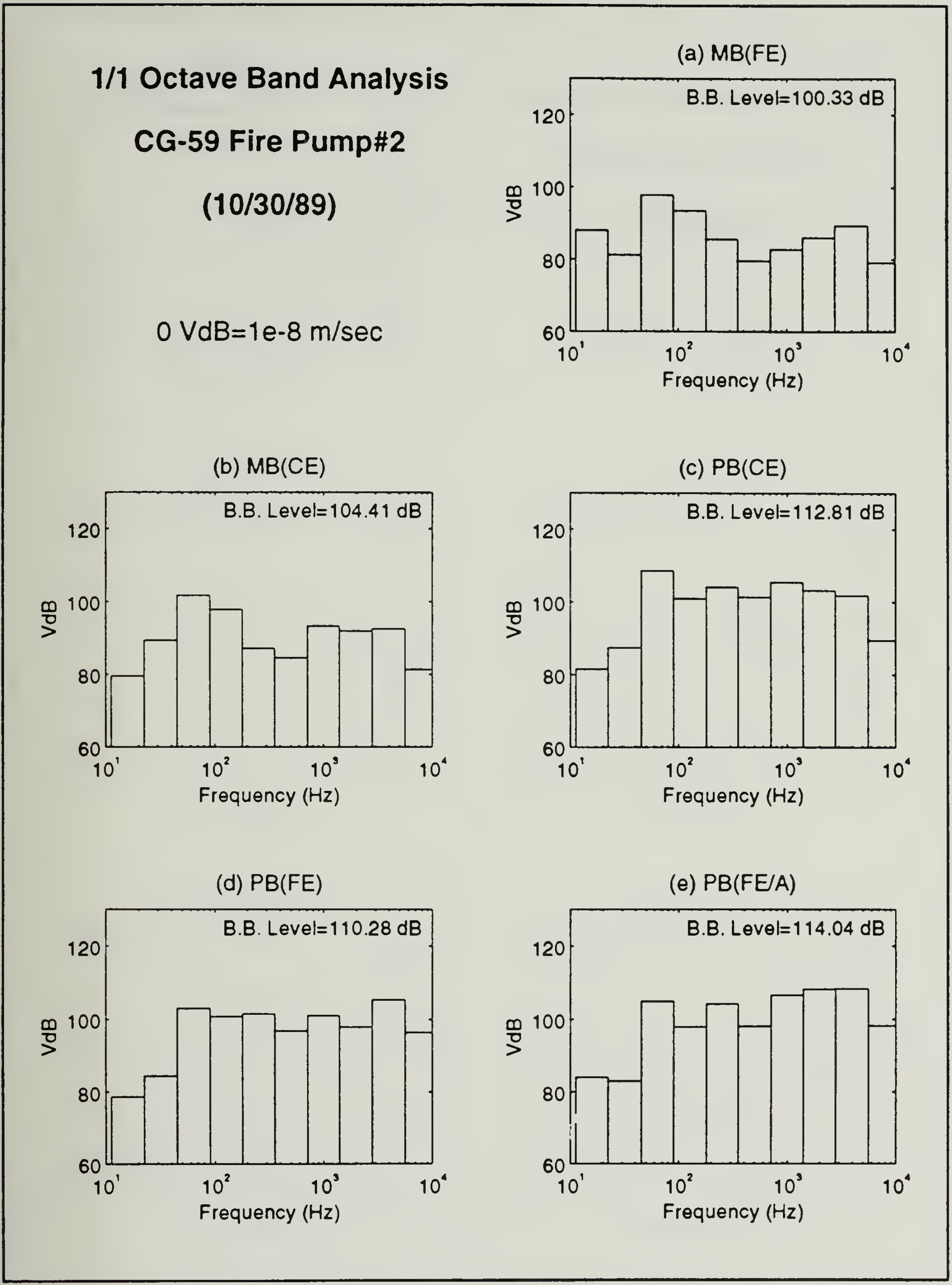


Figure F.23 The 1/1 Octave Band Analysis Results for CG-59 (10/30/89) Fire Pump#2

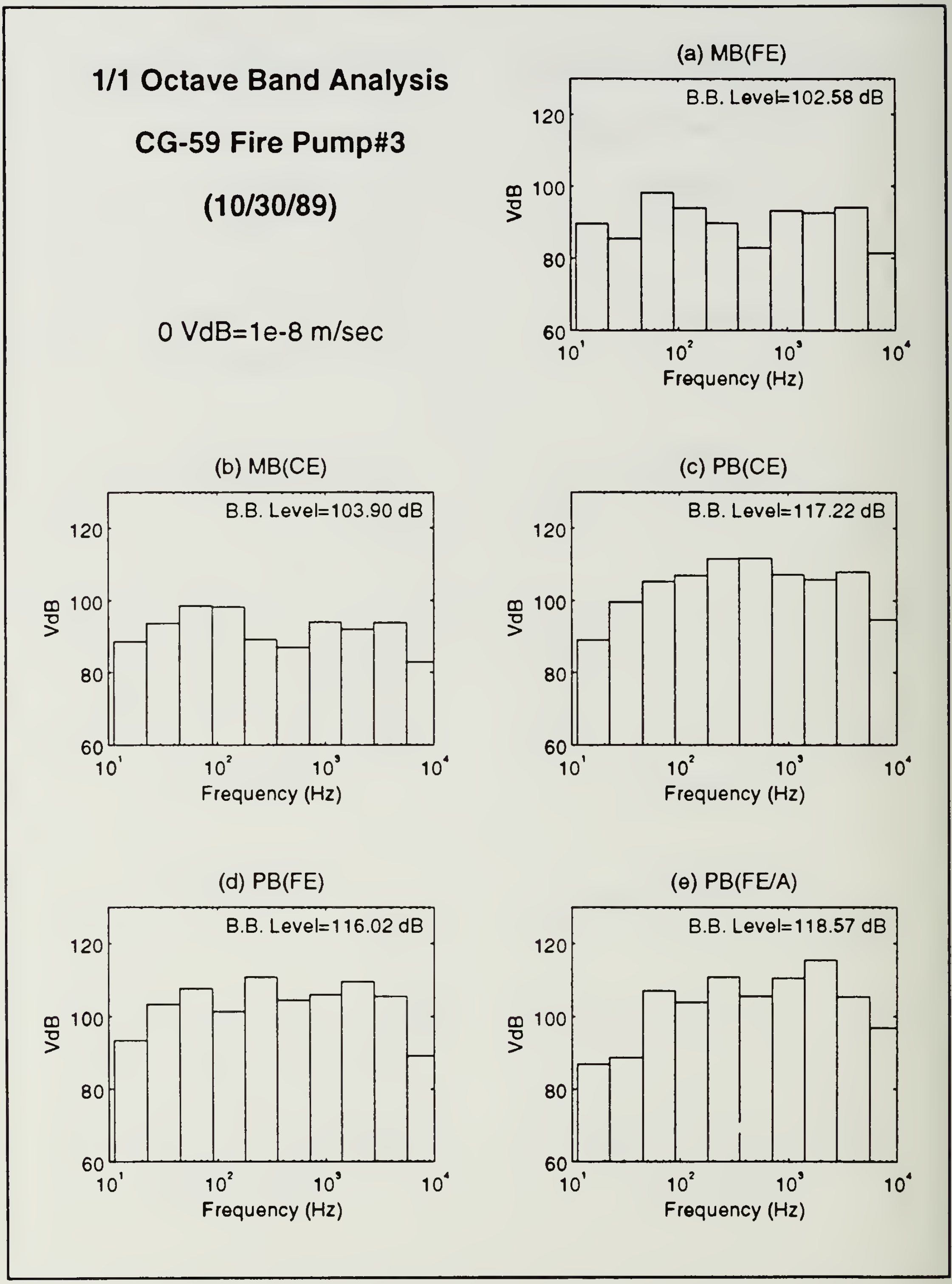


Figure F.24 The 1/1 Octave Band Analysis Results for CG-59 (10/30/89) Fire Pump#3

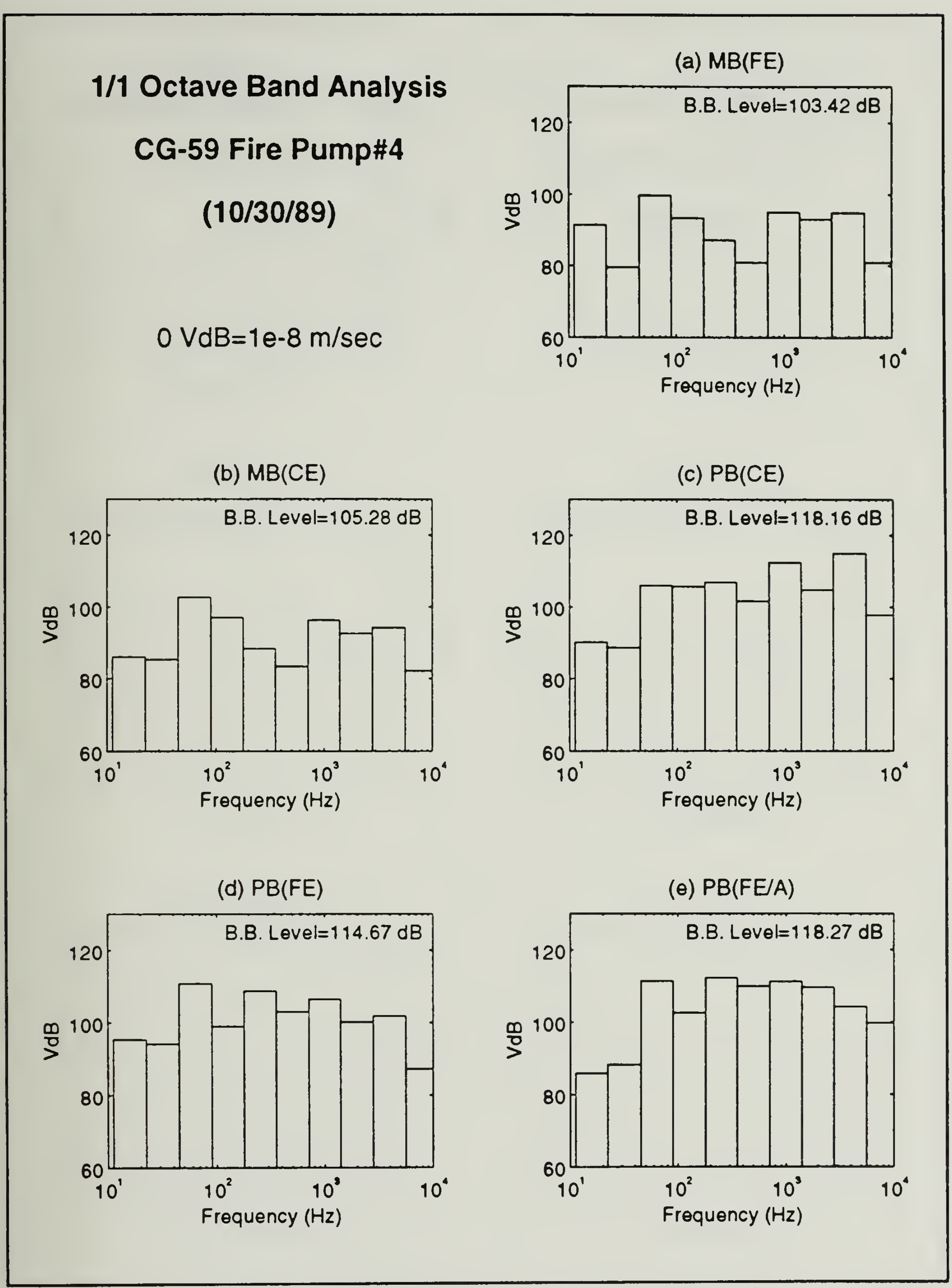


Figure F.25 The 1/1 Octave Band Analysis Results for CG-59 (10/30/89) Fire Pump#4

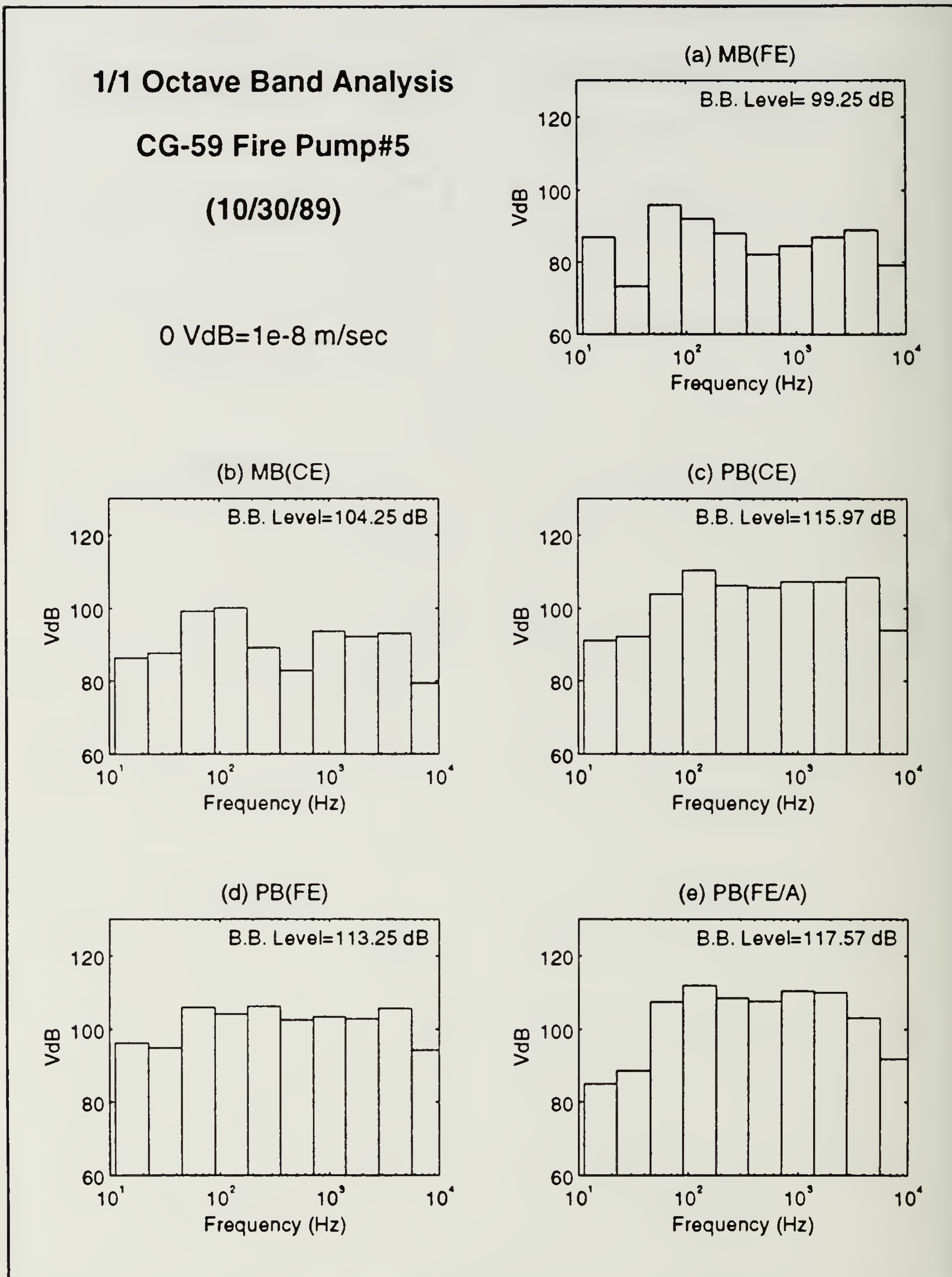


Figure F.26 The 1/1 Octave Band Analysis Results for CG-59 (10/30/89) Fire Pump#5

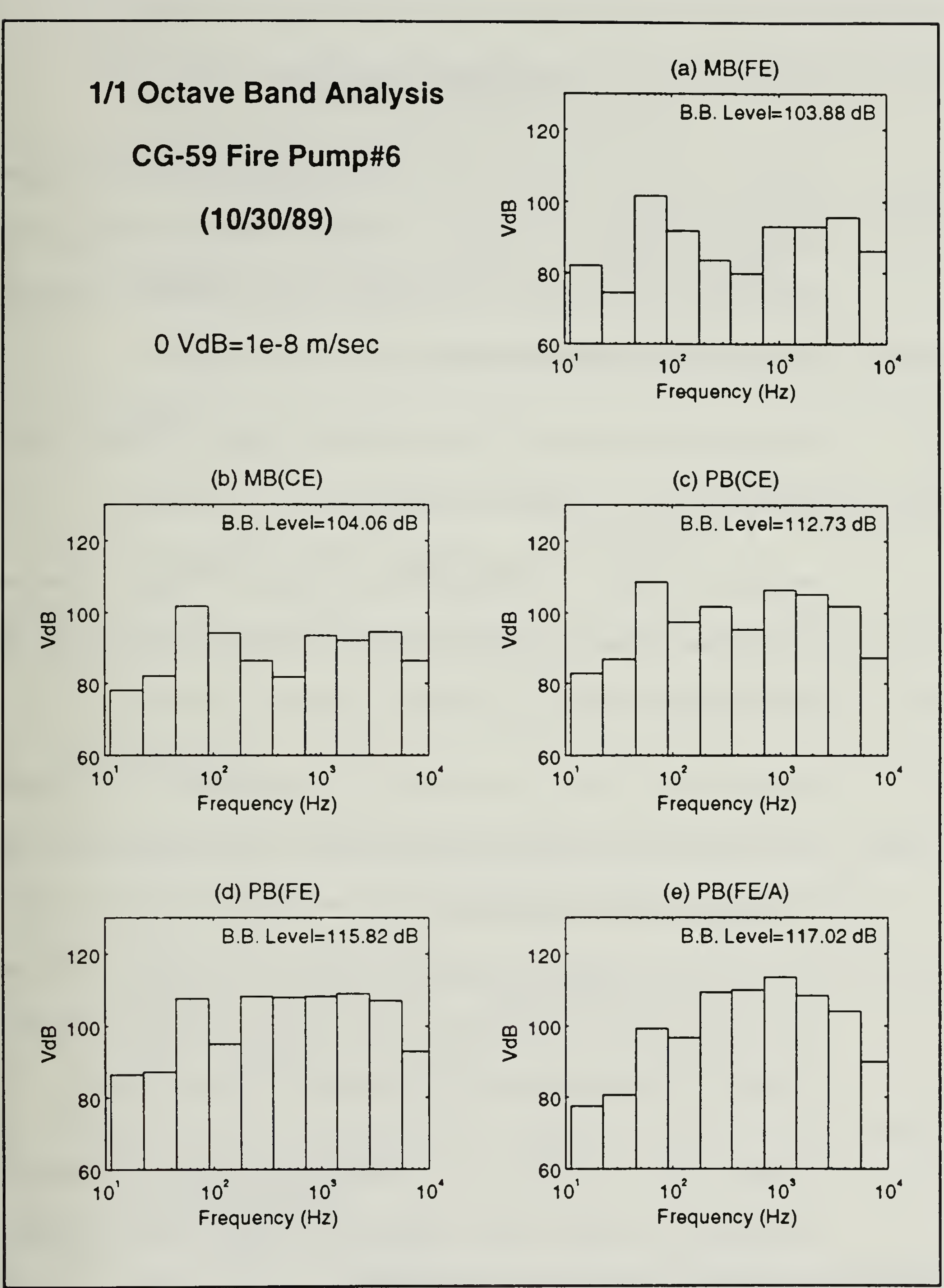


Figure F.27 The 1/1 Octave Band Analysis Results for CG-59 (10/30/89) Fire Pump#6

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